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Energy Procedia 30 (2012) 551 – 561

Energy Procedia

SHC 2012

Validation of the numerical model of a turnkey solar combi+ system

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Abstract

One of the major barriers to a broader market penetration of solar thermal systems is the few information on their long-term performance and reliability. Several works have shown a significant mismatch between foreseen and monitored system performance, mainly due to the lack of an accurate numerical validation analysis or to installation issues. Thus, it is necessary to implement validation and verification processes in the design of solar thermal systems, pointing out quantitative indexes on which a comparison between monitored and simulated outputs has to be based.

This work aims to contribute to the discussion, presenting a numerical validation procedure that can be applied and replicated to any monitored solar thermal system component. In particular, here it is tested to the validation of an immersed heat exchanger of a water storage tank.

The final comparison between monitored and simulated quantities has shown a very good agreement in terms of storage fluid temperatures and heat transfer rate, with a difference of less 2% on the energy exchanged during one exemplary monitoring months.

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Keywords: Numerical model validation; solar combi+ systems; bin method analysis

1. Introduction

Nowadays, a number of 750 solar thermally driven heating & cooling systems are accounted for, with an increase of installations around 30%, between 2010 and 2011 [1]. These systems are not economically attractive yet because of the high investment costs and the relatively few installations set up. In order to promote their market penetration, several projects at international level [2][3] have been launched, tackling design, monitoring and long-lasting quality issues.

A key point for guaranteeing the performance of a solar thermal system is the use of verified and validated numerical models in system simulations; this could (1) promote a more accurate prediction of system's behavior under different boundary conditions, (2) quantify the confidence and build credibility in

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doi:10.1016/j.egypro.2012.11.065

numerical models outputs, (3) solve potential problems before installation and finally (4) aid in decision-making.

A great variety of methods and techniques in numerical model validation have been applied so far in different scientific fields [4]-[8]. Nevertheless, agreement have not been reached on several issues, such as the method to be used for comparing real and simulated systems (qualitative or quantitative) or the amount of data required for the analysis.

The present work aims to contribute in the discussion about numerical model validations. An iterative validation method is here presented and applied as an example for validating the system components of a Solar Combi+ system [9]-[10]. A comparison among expected and actual outputs is reported in order to show the relevance of validation techniques on final energy harvest.

2. Numerical model validation

As a definition, the aim of computer modeling is to replicate the response of real systems under given boundary conditions and for a given set of system parameters. When numerical simulations are performed, it is important to have a clue of the accuracy and the confidence of the outputs with respect to the real performance. The degree of confidence used to state that a numerical model is validated can differ from case to case. A model confidence of 100% is obviously desirable but in most cases the process lead to high costs and be very time consuming. A sufficient degree of confidence must be declared by the user, but a golden rule is not available. For example, in [11] a maximum allowable difference between predicted and monitored data of 15-25% (on a monthly basis) and 25-35% (on a daily basis) for the simulation of HVAC systems is recommended, while with respect to the annual or seasonal period, the simulated outputs should be within 10% and 25%, respectively. Nevertheless, these values should be discussed case by case, accordingly to the needs or the applications.

The model Verification and Validation (V&V) technique is the whole set of steps and processes, which guarantee that a sufficient agreement between the numerical model's and real system' outputs has been reached (Fig. 1). An objective function (known also as cost function) is usually used for minimizing the gap between a given monitored and simulated output [12]. The formulation of this function is crucial and can greatly affect the credibility and acceptability of V&V outcomes. Typically, the minimization of the objective function is carried out on a seasonal or yearly basis and so it could happen that on an instantaneous basis the transient behaviour of a system component is not replicated correctly, even if on an annual basis a good agreement is found.

Traditionally, methods for measuring the accuracy of computational results in solar thermal applications have been either qualitative or semi-quantitative (graph comparison, deterministic approach or mere experimental uncertainty analysis). Arbitrary assumptions can be made along the process and so the implementation of quantitative V&V methods in this sector would be helpful. The major barrier to overcome is the lack of a clear quantitative comparison procedure for achieving a satisfying agreement between simulated and monitored system performance (blue square of Fig. 1): this paper mainly focuses on this issue.

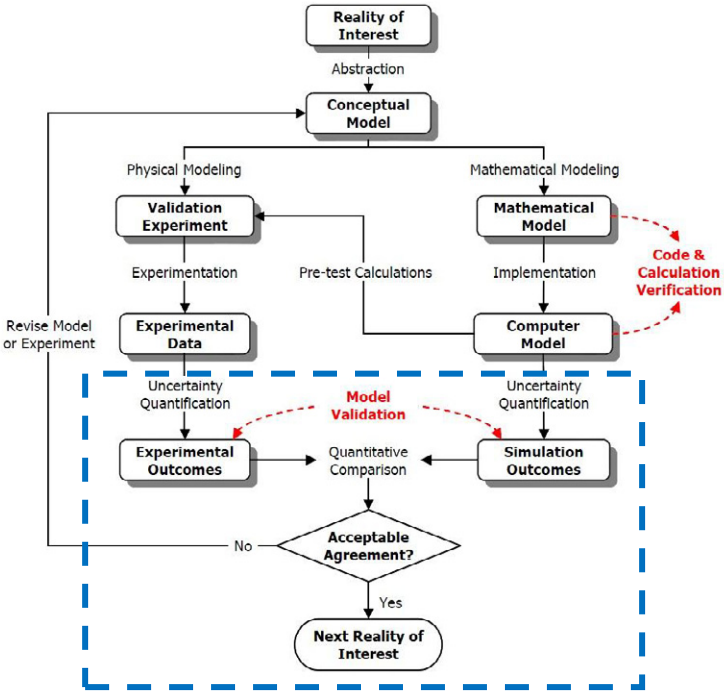

Fig. 1. Detailed model development, verification and validation process [6]

3. A proposal for an iterative validation procedure

The method here presented (see Fig. 2) can be applied for the model validation of a generic energy system when monitoring data and simulation outputs are available. It is an extension of usual V&V methods [13] obtained by integrating new techniques for a more effective and consistent validation result.

As first step, it is essential to gather all the necessary information of the monitoring system set-up (e.g. temperature sensor and flow-meter position, acquisition time step). This phase, defined as "Numerical Model Definition" (see Fig. 2), is essential for defining the outputs and the requirements that the numerical model has to fulfill.

When a large amount of raw monitoring data are collected, it is important to manage them properly from statistical/mathematical point of view. Bin Method Analysis (BMA) [14] is here used as the main technique for data reduction. This technique consists in time-averaging instantaneous monitoring data, with the aim of reducing the influence of unsteady conditions and deriving a clear understanding of the system component behavior. For the application here investigated, a period of 5 minutes has been considered sufficient. The so-arranged data can be further averaged in bins and typical component performance curves (e.g. efficiency curve, heat transfer coefficient, …) can be derived. This analysis can be carried out on raw or post-processed monitoring data, accordingly to the case or the needs. In general, it can be stated that the larger the number of data, the more consistent the output from the BMA. For sake of consistency, each bin has to contain a minimum number of data (greater than 10).

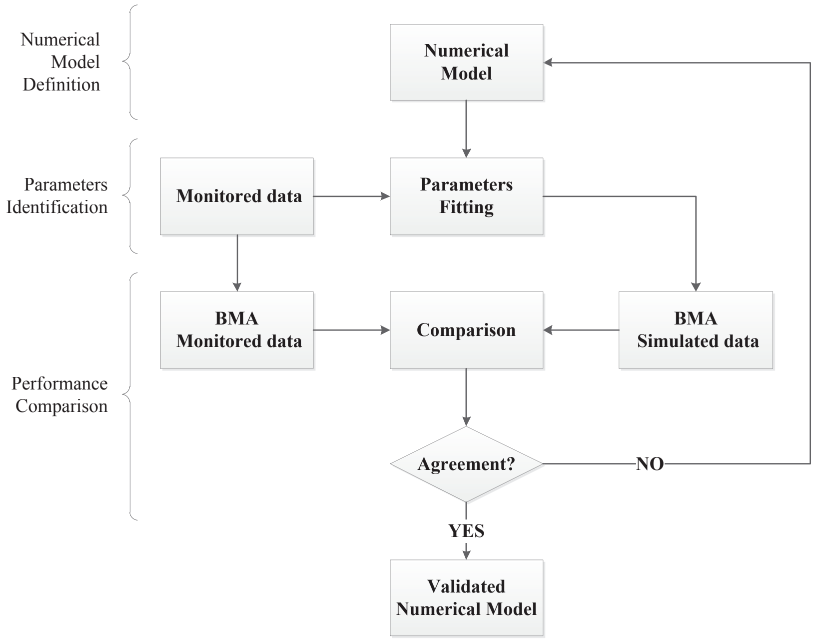

Fig. 2. Iterative validation procedure

In order to test the adherence of simulations to reality, a phase of "Parameter Identification" (PI) (see Fig. 2) follows, where monitoring data (temperatures and mass flow rate) are used as boundary conditions to the simulation models, while simulated and monitored outlets quantities are compared. During the PI, minor component parameters have been varied within realistic bounds, in order to minimize the objective function. The historical data period on which carrying out the PI should represent typical working conditions of the system component [15].

For the present work, a specific objective function OBJ has been developed (equation 1). It is a combination of two correlation coefficients based on the simulated (x) and monitored (y) heat transfer power: the first is known as Pearson product-moment Correlation Coefficient PCC [15] (equation 2) and the second is known as Theil Inequality Coefficient TIC [13][16][17] (equation 3). The objective function OBJ is defined in a way that the optimum value has to tend to 0, when PCC and TIC tend to 1 and 0 respectively.

$$OBJ = 1 - PCC + TIC \tag{1}$$

$$PCC = \frac{n\left(\sum_{i=1}^{n} xy\right) - \left(\sum_{i=1}^{n} x\right)\left(\sum_{i=1}^{n} y\right)}{\sqrt{n\left(\sum_{i=1}^{n} x^2\right) - \left(\sum_{i=1}^{n} x\right)^2}\sqrt{n\left(\sum_{i=1}^{n} y^2\right) - \left(\sum_{i=1}^{n} y\right)^2}} \tag{2}$$

$$TIC = \frac{\sqrt{\sum_{i=1}^{n} (x-y)^2}}{\sqrt{\sum_{i=1}^{n} x^2} + \sqrt{\sum_{i=1}^{n} y^2}} \tag{3}$$

When the PI converges towards the minimum, the maximum agreement has been found. This however, does not say anything on the accuracy of the model. Therefore, a comparison of the numerical results with the monitoring data has to be performed on the basis of quantitative performance figures. To this purpose, a further BMA is made on the simulation outputs. A quantitative comparison among the monitoring and simulated BMA curves is then performed ("Performance Comparison", see Fig. 2). If the Root Mean Square Error (RMSE) value of the curves is within the acceptance criterion defined by the user, then the validation is accomplished, otherwise the numerical model has to be revised or upgraded. This process is repeated until an adequate level of agreement is found.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (x-y)^2}{n}} \tag{4}$$

4. Application of the methodology to a case study

The method has been tested on the validation of an immersed coil heat exchanger (IHX) in a solar water storage, which is a part of a more complex plant layout [9][10] (Fig. 3). This is a Solar Combi+ system, aiming at covering DHW, space heating and cooling loads typical of residential buildings. A prototype of the plant is placed in Bolzano (Italy) and it has been monitored since July 2011.

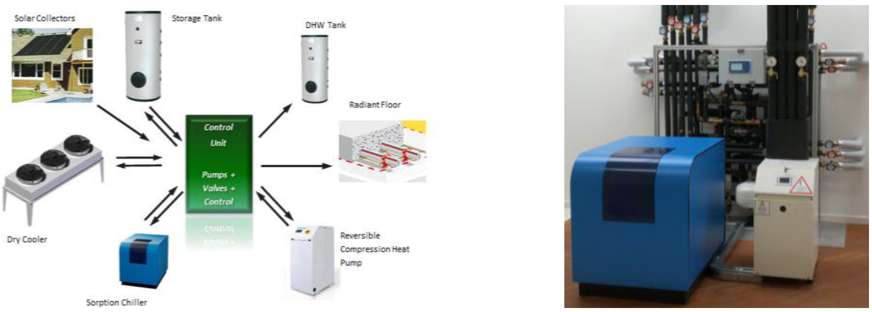

Fig. 3. Solar Combi+ system layout (a) and installation (b)

The sub-system under investigation (Fig. 4) is made by a solar-thermal field with an aperture area of 32.4 m^2, connecting 16 flat-plate collectors in parallel. A mixture of propylene glycol (30%) and water is used as working fluid. The mass flow rate can vary up to 1300 kg/h, accordingly to the control strategy. As shown in Fig. 4, the solar-thermal field raises the temperature of the water storage with a capacity of 500 liters. An immersed heat exchanger is used for transferring the collected solar energy to the water tank, while a direct port is adopted for extracting a variable mass flow $\dot{m}_{load}$. The geometrical parameters provided by the water storage manufacturer are listed in Table 1.

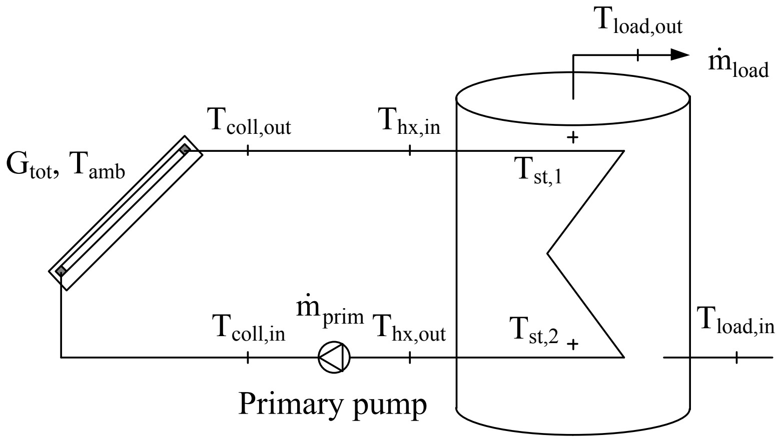

Fig. 4. Solar system under investigation

Table 1. Geometrical characteristics of solar water storage

	Value
Capacity [l]	500
External diameter [mm]	650
Height [mm]	1545
Insulation thickness [mm]	50
Temperature sensors positions [-]	0.87 – 0.13
Heat exchanger	
Inlet position [-]	0.83
Outlet position [-]	0.13
Volume [l]	42.6

5. Analysis of the heat exchanger

In general, one of the major issues in validating the storage components is the definition of the overall heat exchange coefficient UA_{hx} of an IHX [18][19]. In general it is a space-time-variant parameter, which depends from on the working conditions (mass flow rate and/or temperature). These dependencies can be quantified performing laboratory tests accordingly to the European standard EN 12977-4 [20]. In most cases, when tests are performed, the results are not always publically available, because manufactures prefer to show the amount of delivered energy at a given fluid temperature and for a given degree of stratification in the storage. Thus, a procedure for quantifying the actual UA-value of the heat exchanger from in-situ data is very useful.

In this work, the numerical simulation of the solar water storage have been carried out by using the Type 340 [21] of Trnsys simulation software [22]. It permits to simulate stratified fluid storage tanks with direct ports for charging/discharging purposes and different configurations of immersed coil heat exchangers. A fully mixed or stratified storage can be chosen by setting the number of internal nodes n_{hx} in which the storage is divided: the greater the number, the better the accuracy, but the higher the computational effort.

In Type 340 an empirical relationship (equation 5) is used to quantify the UA-value.

$$\frac{UA_{hx}}{n_{hx}} = \frac{\overline{UA}_{hx}}{n_{hx}} \cdot F_{hx} \cdot \dot{m}_{hx}^{b_{hx,1}} \cdot \left[\vartheta_{hx,in} - \vartheta_{st,j}\right]^{b_{hx,2}} \cdot \left[\frac{\vartheta_{hx,in} + \vartheta_{st,j}}{2}\right]^{b_{hx,3}} \text{ with } j = 1, \ldots, n_{hx} \quad (5)$$

From a physical point of view, the overall heat transfer coefficient UA_{hx} is based on three heat transfer resistance in series: (1) the heat transfer resistance between the inner IHX fluid and the pipe wall (forced convection), (2) the conductive heat transfer within pipe wall and the heat transfer between the outer IHX pipe and (3) the storage fluid (natural convection). Because of the high-conductive material of immersed coil, the heat transfer resistance through the coil wall is assumed to be negligible, so that the final UA_{hx} calculation will result from the following equation.

$$\frac{1}{UA_{hx}} = \frac{1}{UA_{hx,int}} + \frac{1}{UA_{hx,ext}} \quad (6)$$

The internal heat transfer coefficient $UA_{hx,int}$ is mainly influenced by the Reynolds number Re (by the mass-flow rate), while the external heat transfer coefficient $UA_{hx,ext}$ by the Grashof number Gr (by the temperature difference between the pipe wall and storage fluid).

Referring to the notation shown in Fig. 4, the influence of the mass-flow rate on the overall heat transfer coefficient UA_{hx} can be derived from monitoring data and by highlighting the following relationship:

$$UA_{hx} = \frac{\dot{Q}_{hx}}{LMTD} \quad (7)$$

where:

$$\dot{Q}_{hx} = \dot{m}_{hx} c_{p,g} \left(T_{hx,out} - T_{hx,in}\right) \quad (8)$$

The calculation of the LMTD has been made by assuming as heat exchanger hot side the IHX fluid, while as cold side the storage fluid. The position of the temperature sensors $T_{st,1}$ and $T_{st,2}$ into the storage tank is such that they can be used as cold outlet and inlet section, respectively.

$$LMTD = \frac{(T_{hx,in} - T_{st,2}) - (T_{st,1} - T_{hx,out})}{\ln \frac{T_{hx,in} - T_{st,2}}{T_{st,1} - T_{hx,out}}} \tag{9}$$

For sake of clarity, equation 5 can be manipulated by using a logarithmic notation as follows:

$$\log UA_{hx} \cong \log \overline{UA}_{hx} + b_{hx,1} \cdot \log \dot{m}_{hx} \tag{10}$$

This dependency has been shown in Fig. 5, where the BMA curve has been derived on monitored data. This analysis have been conducted on approximately 17400 points, which have been time-averaged on 5 minutes (blue dots). From these a BMA curve (red curve) have been derived and then fitted with a linear regression.

The correlation has been used in PI analysis, by setting $\overline{UA}_{hx} = 10^{3.5891} = 3882$ W/K and $b_{hx,1} = 0.9102$. This permitted to reduce the number of free parameters investigated during the PI, limiting the analysis to F_{hx}, $b_{hx,2}$ and $b_{hx,3}$, with the consequence of reducing the computational effort.

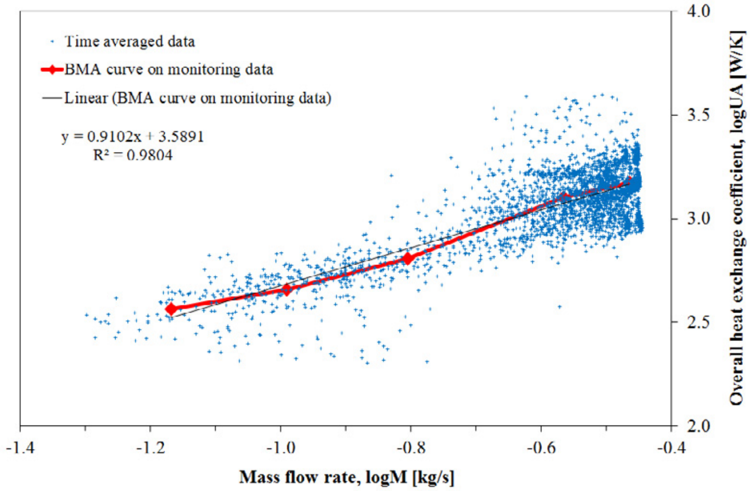

Fig. 5. BMA curve on monitored data

The results derived from the PI have been used in simulations and a quantitative comparison have been performed. The quantitative comparison between the two BMA curves of UA_{hx} showed a RMSE value of 1%, therefore it is not reported on the chart Fig. 5 because it can not be distinguished. The V&V procedure has reached a very good agreement in terms of istantaneous temperature profiles and heat transfer rates between simulated and monitored outputs. This is shown in Fig. 6 and Fig. 7 where both quantities have been graphed (1 minute time step) for the measured conditions of the 18th December 2011.

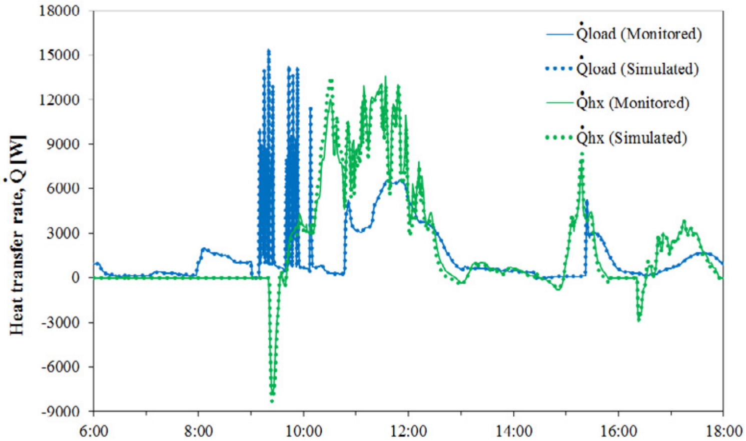

Fig. 6. Comparison between monitored and simulated profiles of $\dot{Q}_{load}$ and $\dot{Q}_{hx}$ (18th of December 2011)

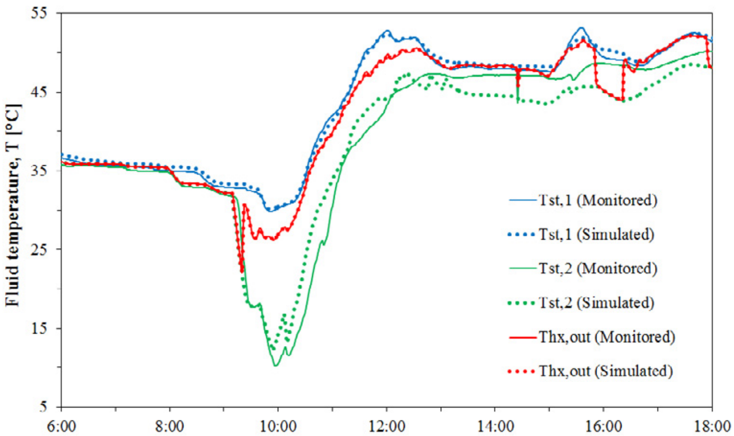

Fig. 7. Comparison between monitored and simulated profiles of storage temperature sensors ($T_{st,1}$ and $T_{st,2}$) and outlet fluid temperature from IHX ($T_{hx,out}$) (18th of December 2011)

On a 30-days period (December 2011), the energy measured by the monitoring system from the solar field to the water storage was 565.02 kWh, while the simulated value differed less than 2% (Table 2). The same calculation have been performed on the energy transferred from the water storage to other system processes: here the discrepancy is a little higher but however always within acceptability limits.

Table 2. Comparison between validated numerical model and monitoring data in terms of energy transferred over 30-days period (December 2011) length

	Monitoring	Simulation	ΔQ [%]
Q_{hx} [kWh]	565.02	555.95	-1.6
Q_{load} [kWh]	508.94	483.25	-5.0

6. Conclusions

Validation and Verification (V&V) techniques are essential measures to ensure consistency of design performance of solar thermal systems. These activities permits a better confidence and reliability on expected behavior under different boundary conditions, leading to a better market penetration of solar renewable technologies.

The work has presented a procedure for validating system components used in numerical simulations. The method has been applied to the validation of an immersed heat exchanger of a water thermal storage. Bin Method Analysis [4] has been used as main data reduction technique: it has permitted to derive typical system performance curves from monitoring data or from system numerical simulation outputs. A Parameter Identification (PI) [12] technique has been used for tuning minor component coefficients, by means of minimizing a user-defined objective function. A quantitative comparison in terms of Root Mean Square Error (RSME) between BMA curves based on simulation and monitoring outcomes permitted to guarantee that an adequate agreement has been achieved. In other cases, the process must be repeated until adequate agreement is not found by modifying the numerical model.

Even if a very good agreement has been found between real and simulated values (a divergence of 2% and 5% on the energy transferred by the IHX and the direct port), there are still several aspects to be more accurately addressed, in particular (1) the definition of the minimum monitoring period length on which the BMA curve has to be calculated from monitoring data; (2) the formulation of the most appropriate objective function to be used in the PI, its influence on converging to the optimum configuration and the monitoring quantity (e.g. heat transfer rate, temperature) to be used for the comparison; (3) the minimum simulation period on which the PI is carried out and its influence on converging to the optimum configuration.

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