# Advanced Process Control of Distributed Parameter Plants by Integration First Principle Modeling and Case-Based Reasoning

## Part 2: Case-Based Reasoning Control of DPP

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***Abstract* — The Case-Based Reasoning (CBR) as a tight integration of the model-based and data-driven approaches in optimization and control of plants with distributed parameters (DPP) is considered into this second part of the paper. The main pecularities of the adopted modifications of CBR in accordance of the area of application are examined – structuring of search space as virtual version space, retrieval for different form of attribute-value presentations, efficient indexing and adaptation using local regression in order to improve retrieved solution into the direction to obtain query problem solving. The main results of the accomplished simulations are reported focusing both the maximum capacity and minimum heat consumption. The results show that suboptimal control of TTP based on modified CBR is a reasonable approach.**

***Keywords – Case-Based Reasoning; Energy Efficiency; Indexing; Optimization; Regression; Retrieval***

## I. Introduction

The interest toward Case-Based Reasoning grows significantly during the last two decades because of the continuous extension of the scope of its successful applications. One of the main reasons for this progress represents fast improvement in the theoretical and computational level of each of the stages of the traditional $Re^4$ cycle: Retrieval, Reuse, Revising, and Retain [1, 2]. At the same time a number of new CBR modifications appear: optimization of internal procedures of CBR [3]; dynamization of CBR via Dynamic CBR and Process oriented CBR [4, 5]; new algorithms with structured cases [5]; new achievements for cases indexing [6, 7]; more fast and relevant to the corresponding domain methods for retrieval and querying [2, 3, 5]. Some new results appear in the application of CBR in the solving control problems of sophisticated complex systems [8, 9].

Following the theoretical approach proposed in the first part of this investigation [10] for the case of Thermal Treatment Process (TTP) control, the CBR is applied as a tool for tight integration of the model-based and data-driven approaches.

The problem consists to find an appropriate solution for given operational conditions (batch parameters, dispatching commands, and operator's preferences) as close as possible to preliminary generated virtual points in a Version Space (VS) via retrieval and consequent adaptation to solve the initial query problem. The control scheme is accepted as an open loop structure with adaptation from batch by batch.

The accepted control algorithm could be bidirectional – minimum time process ($J_1$) or maximum thermal efficiency ($J_2$). The simulation results confirm the efficiency of the adopted approaches.

## II. Case-Based Reasoning as a Tool for Tight Integration

### *2.1. Case-Based Reasoning (CBR) Formulation for Distributed Parameter Plants Control*

CBR as one of the widely used techniques of AI [2] is applied in the present study as an instrument to integrate model-based and data-driven approaches. Because the available for CBR data in our domain of interest as a result of time consuming off-line computer calculations of two sequential tasks – first solving the mathematical model presented via First Principle method obtained nonlinear Partial Differential Equations and second – deriving optimal or suboptimal open loop TTP control using constrained nonlinear optimization problem will be of a modest volume.

Thus as an appropriate model of CBR we accept CBR process model, which contains: problem formulation, $Re^4$-sequential CBR stages, and storage the new information for the fulfilled batches. In this form of application CBR possesses important peculiarity – the possibility to operate with a small or medium sized data set. Thus it is expedient for the solving our task. CBR is directed to find solution $S^N$ of a new arising problem $P^V$ using the similarity with yet existing

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case in the Case Base (CB). In established form of presentation [1, 2, 3] it could be written as

$$C^{CB} = \langle P^{CB}, S^{CB} \rangle, \tag{1}$$

where P is the problem; S – solution.

If we could find case where $P^{CB} \approx P^{N}$ we believe that $S^{N}$ will be similar to $S^{CB}$ ($S^{B} \approx S^{CB}$). In our study the problem is presented in the following form:

$$P^{N} = (\pi^{N}, a^{N}, \gamma^{N}, w^{N}) \tag{2}$$

and the solution represents the parameters of the control variable trajectory

$$S^{N} = (\tau_i^{N}, t_{mi}^{N}, \tau_f^{N}) \quad (i = 2, 3, 4). \tag{3}$$

In accordance with our control-oriented goal, the CBR module could be represented in following two forms (Fig. 1):

a) Static CBR – traditional CBR structure [1, 2, 3];

b) Process oriented CBR – PO-CBR structure [4, 5].

In contrast to traditional static CBR presented with eq. (1), the dynamic form of CBR comprising components (2) and (3)

$$C^{N} = (P^{V}, S^{V}) \tag{4}$$

persists dynamic extension of CBR [4, 5].

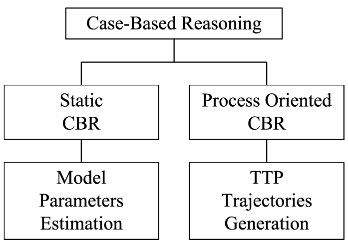



Figure 1. Two ways to use CBR in APC

### 2.2. CBR-based hybrid control system

The functional scheme of the proposed hybrid control system is presented on Fig. 2. Following the framework of the suggested approach [10] in sequential stages of the TTP control and in dependence of the accepted objective function ($J_1$ or $J_2$) different elements P and S are used into the retrieval process.

The accepted in this study variant of CBR implementation simplifies all its stages: creation of well structured Version Space (Fig. 6 in [10]); rational indexing of Cases; fulfilling usual $R^4$ cycle of CBR [1]; maintenance of CB, which is invariant concerning accepted wood species $\pi_i$ ($i = 1, N$).

### 2.3. CBR indexing

As the indexing of the cases in CB is very important for the efficient retrieval [6, 7], in this study it is integrated with adopted model parametrization and the signal-based measurement level ($\pi$, $a$, $\gamma$, $w$) is combined with the control oriented functional level ($t_{mi}$, $\tau_{mi}$, $\tau_f$). In this way the accepted operational situation relevant indexing strongly effects on the flexibility, reliability, and robustness of the fulfilled open loop suboptimal control strategy of TTP.

Following our focus on structuring CB and CBR in accordance with the similarity of the current situation with the

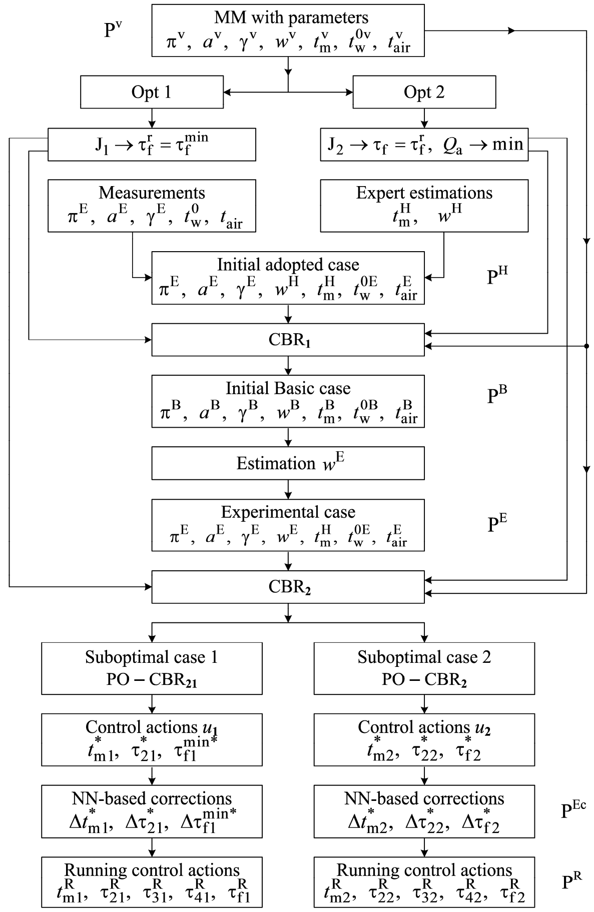



Figure 2. Flowchart of CBR-based hybrid control system

nearest simulated VS case results in suitable CB configuration, which improve the performance of the reasoning process in CBR.

### 2.4. Retrieval process

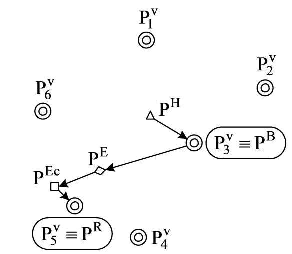
Retrieval efficiency is of critical importance for CBR functionality [2, 3, 5] in order to improve the similarity assessment. In accordance with the procedure presented on Fig. 2, the corresponding retrieval process is shown on Fig. 3. Here $P^{V}$ is the problem parts of the cases in VS and $P^{H}$, $P^{B}$, $P^{E}$, $P^{Ec}$, and $P_R$ is the sequence of the problem parts of a real batch in different stages of CBR procedure (Fig. 4).

On Fig. 4 the optimization step of the solution $S^{R}$ in both cases with objective functions $J_1$ and $J_2$ is presented.

### 2.5. Correction of the operational references

In order to reduce significantly the volume of the search space VS, the two batch parameters $t_w^{0}$ and $t_{air}$ with secondary importance are taking into account via correction of the vector $P^{E}$ determined by the retrieval (Fig. 5):

$$P^{Ec} = P^{E} + \Delta P^{E}. \tag{5}$$




$P_i^v \to P^H \to P^B \to P^E \to P^{Ec} \to P^R$

Figure 3. Successive steps in the retrieval in VS

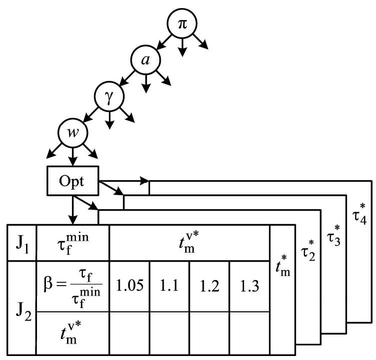



Figure 4. Optimization step

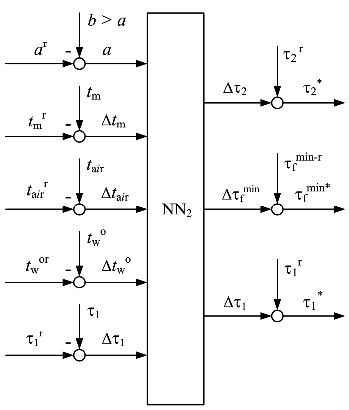



Figure 5. Operational references correction

The correction $\Delta P^E$ is carried out using neural network ($NN_2$) learned locally. It is schematically presented on Fig. 5.

## III. Local Regression

Regression calculations are fulfilled using off-line received simulation results following known methodology [11, 12, 13].

a) The correct value of the batch moisture content of the wood materials is of critical importance for the modeling and prediction of TTP but unfortunately its direct measurement is impossible. Because of that an identification step is stipulated (Fig. 2) in the following sequence:

- Parametrical vector $P^H$ is formed, where $t_{w0}$ expert value estimation exists for $w^H$ and $t_m^H$ (usually $t_m^H = t_m^{max}$):

$$P^H = (\pi^E, a^E, \gamma^E, w^H, t_m^H), \quad (6)$$

- Using retrieval procedure in $CBR_1$, the nearest basic vector $P^B$ from VS is found.

- With the maximal available value of $t_m^R = t_m^{max}$ the TTP is starting up and the initial heating trajectory is formed:

$$t_m^E(\tau) = f_E(P^H, w^E), \quad (7)$$

where the wood moisture content $w^E$ is unknown.

- From CB the transient process, corresponding to the vector $P^B$, is found out in the form of

$$t_m^B(\tau) = f_B(P^B, w^B). \quad (8)$$

- In the difference of two trajectories (7) and (8):

$$\Delta t_m(\tau) = t_m^E(P^H, w^E) - t_m^B(P^B, w^B) \quad (9)$$

the only moisture content $w^E$ is unknown and it could be determined using the following regression:

$$w^E = R(P^H, P^B, \Delta t_m(\tau_i)) \quad (i = 1, 2, \dots, n),\ 0 < \tau_i < \tau_1. \quad (10)$$

b) The minimum duration of the TTP, $\tau_f^{min}$, for each given heating temperature $t_m$ could be found from the cases in the Version Space (VS). In accordance with Fig. 4, for each vector $P^v = (\pi^v, a^v, \gamma^v, w^v)$ and using 4 temperatures for $t_m$ ($t_m$ = 130, 120, 110, 100 °C) it could be found four values for the duration $\tau_f^{min}$. Using these discrete values the next regression could be determined:

$$\tau_f^{min}(t_m) = R_f(P^v, t_m). \quad (11)$$

On Fig. 6a the regression curves 1 and 2 present the relation (11) for the objective functions $J_1$ and $J_2$ respectively. As it is shown on Fig. 6b, the starting up of the TTP with the highest available temperature $t_m^R(0) = t_m^{max}$ results in shortest TTP but in higher energy consumption $Q_a$ and lower efficiency coefficient $\eta$.

c) In analogical way it could be obtained the following regressions:

$$\tau_2^{min} = R_2^{min}{}_f(P^v, t_m), \quad (12)$$

$$\tau_2^{opt} = R_2^{opt}{}_f(P^v, t_m) \quad (13)$$

for the objective functions $J_1$ and $J_2$ respectively as it is presented from the regression curves on Fig. 7.

## IV. Integrated Hibrid Control System

The generalized functional scheme of the proposed hybrid control system is shown on Fig. 8. A number of nontrivial procedures are integrated: Simulation, Parameter estimation, CBR, Regression analysis in order to improve the accuracy into the existing and new situations, Two-criterion Optimization, and Adaptation.

More detailed scheme with explicit representation of the interconnections is shown on Fig. 9. It can be seen that into the proposed system a CBR in three different modifications has

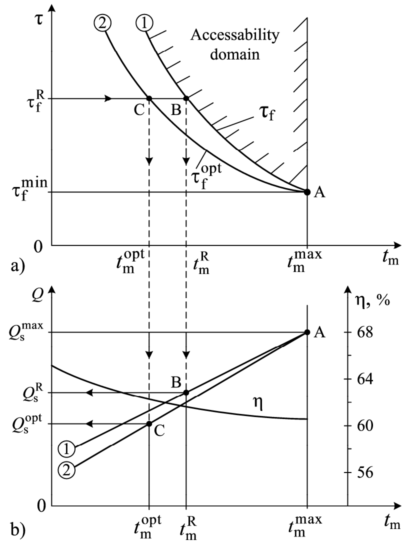



Figure 6. Local regressions: a) Duration: 1 - $\tau_f$ , 2 - $\tau_f^{opt}$ ;
b) Energy consumption $Q_a$ and efficiency coefficient η

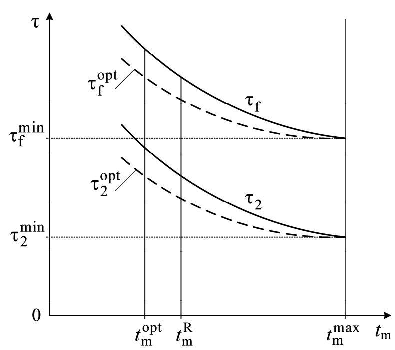


Figure 7. Local regressions $\tau_f$ , $\tau_f^{opt}$ , $\tau_2$ , $\tau_2^{opt}$

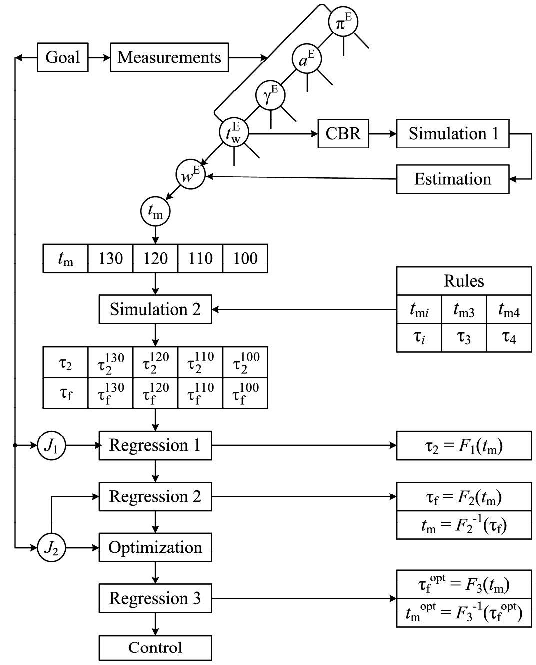



Figure 8. Generalized functional scheme of the proposed hybrid control system

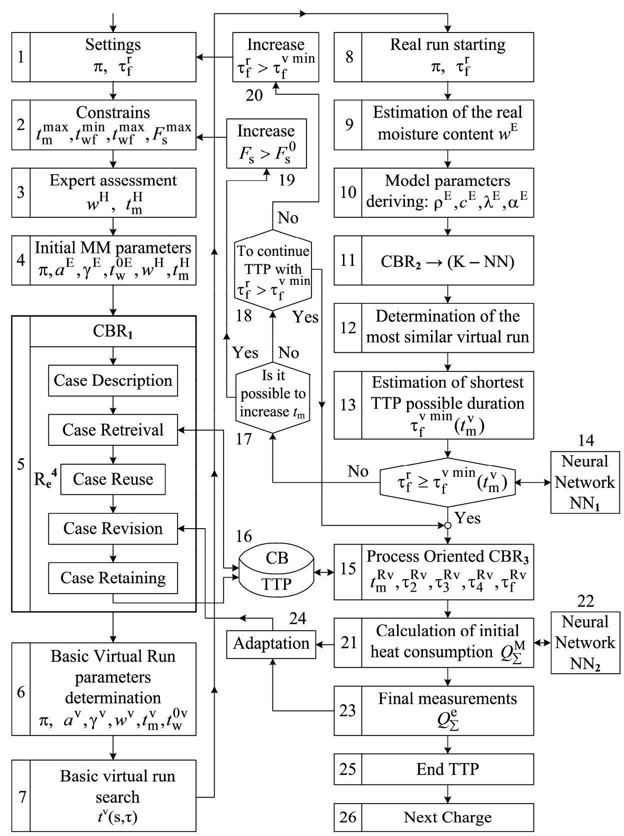



Figure 9. Detailed procedural scheme of the proposed control system

been used: $CBR_1$, $CBR_2$, and Process Oriented CBR. The adaptation module with number 24 modifies the retrieves solution $S^V$ in order to improve the control behavior. In this way the retrieved solution could be transformed as a solution of the original query problem. Due to the fulfilled correction from batch to batch as slow parametrical feedback, during time this leads to increasing the efficiency of the control system.

## V. Simulation Results

### *5.1. Simulation framework*

a) Computer simulations are carried out using developed mathematical model of the Thermal Treatment Process [14]. For the thermal efficiency determination are implemented static models and procedures given in [15, 16].

b) Simulation calculations are focused in two directions:

- System behavior subjected to optimization criterion $J_1$;
- System performance in accordance with the criterion $J_2$.

c) All simulations are realized under the next assumptions:

- 2D non-stationary heat transfer process is considered;
- Boundary conditions are equal for all batchd materials;
- The heated materials have the same dimensions.

### *5.2. Control system performance under objective function $J_1$*

a) Fig. 10 represent the transient behavior of TTP for variety of batch parameters (a, $\gamma$, w, $t_m$) for beech wood.

b) At Fig. 11 and Fig. 12 the trajectories of the energy consumption $Q_w$ and $Q_a$, and also heat flow $q_{ha}$ are presented.

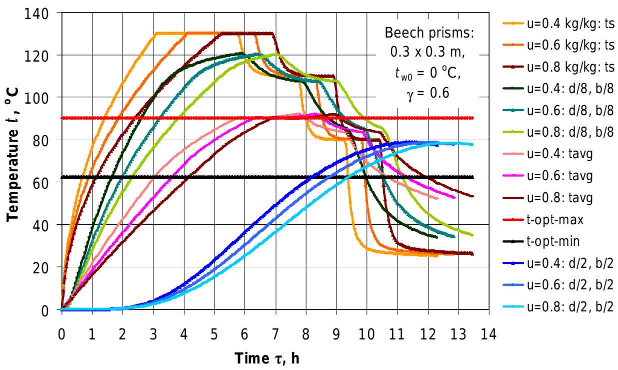



Figure 10. Transient trajectories in different critical points in TTP of beech prisms with cross-section dimensions 0.3 x 0.3 m and $\gamma$ = 0.6

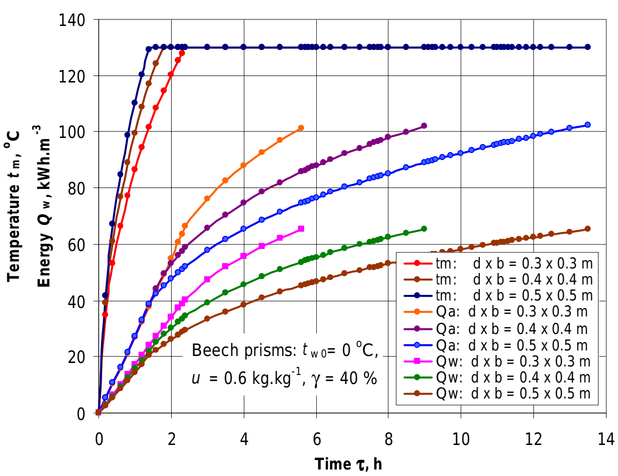



Figure 11. Dynamic behavior of $t_m$ and energies $Q_w$ and $Q_a$

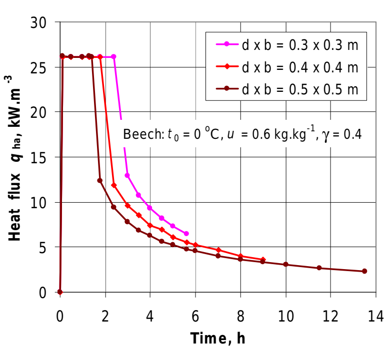



Figure 12. Heat flux during the TTP

### *5.3. System behavior under objective optimization function $J_2$*

In dependence of the stage of the TTP three different variants of CBR are applied (Fig. 9) with the next attribute-value (AV) parameters (Table 1);

Table 1. Attribute-value parameters

| | AV | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $CBR_1$ | $AV_1$ | $\pi$, $a$, $\gamma$, $w$, $t_m$ | | | | | | | |
| $CBR_2$ | $AV_2$ | $AV_1$ | $\tau_1$ | $\tau_2$ | $\tau_3$ | $\tau_4$ | $\tau_f$ | | |
| | | | $t_{m1}$ | $t_{m2}$ | $t_{m3}$ | $t_{m4}$ | $t_{mf}$ | | |
| $CBR_3$ | $AV_3$ | $AV_1$ | $\tau_1$ | $\tau_2$ | $\tau_3$ | $\tau_4$ | $\tau_f$ | $\tau_4$ +1h | $\tau_4$ +2h |
| | | | | $t_1$ $t_4$ $t_{avg}$ $Q_w$ $Q_a$ | $t_{m3}$ | $t_1$ $t_4$ $t_{avg}$ | $t_1^f$ $t_4^f$ | $t_1$ $t_4$ | $t_1$ $t_4$ |

Small part of the Version Space formation under $J_2$ criterion via simulation is presented in Table 2. It corresponds to Process oriented CBR($AV_3$). As it can be seen in particular cases the key temperatures $t_1(\tau_f)$ and $t_4(\tau_f)$ could violate the reference thresholds $t_1(\tau_f) > t_1^{R\max}$ and $t_4(\tau_f) < t_4^{R\max}$.

In Table 3 for the same operational conditions as in Table 2 are represented the input heat $Q_a$, used heat energy $Q_w$, and the heat efficiency $\eta$ in corresponding attributes of $CBR_3$.

Based on Version Space with 256 virtual versions some conclusions could be derived:

1. Structural organization of the Version Space as a Case Base (CB) for CBR is relevant in use.
2. Discretization of the Version Space via 4 – 5 values for each attribute guarantees sufficient accuracy.
3. In dependence on the type of CBR application during the TTP stages both the local similarities and global similarity should be execute. The useful weights $\alpha_i$ for TTP could be accepted for the main attributes into the following ranges: $\alpha_a$ = 0.35 ÷ 0.4; $\alpha_\gamma$ = 0.15 ÷ 0.2; $\alpha_w$ = 0.2 ÷ 0.25; $\alpha_{tm}$ = 0.25 ÷ 0.3.
4. The change of the operational conditions at the end of the TTP ($\tau > \tau_4$ – refer to Fig. 4 in [10]) makes reasonable to incorporate some knowledge-based rules.
5. The increasing of the wood moisture content $w$ from 0.4 to 0.8 kg·kg$^{-1}$ causes an improvement of the efficiency $\eta$ in the range from 2 to 4%.
6. The increasing of the relative degree of batch loading $\gamma$ from 0.4 to 0.6 increases the efficiency $\eta$ up to 4%.
7. Each increase of $\gamma$ by 0.1 at given value of $w$ causes an increase of the duration of the TTP regime by 0.1 h.
8. In a case of indispensable batch of both more massive and thinner materials the biggest admissible size difference must not exceed 0.1 m.

## VI. CONCLUSIONS

For technological processes, where the space distribution of the parameters is of critical importance for the accuracy, capacity, and resources' consumption, the proposed suboptimal control strategy retains the efficiency of the model-

Table 2. Transient behavior

| Simulation conditions: $d$ x $b$ = 0.5 x 0.5 m, $t_w^0$ = 0 °C, $t_{m1}$ = 110 °C, $t_{m2}$ = 100 °C, $t_{m3}$ = 80 °C, T$_1$ = 1800 s, T$_2$ = 10 s, T$_3$ = 1030 s, T$_4$ = 990 s, T$_5$ = 600 s | | | | | |
|---|---|---|---|---|---|
| **$w$, kg·kg$^{-1}$** | **$\gamma$, -** | **$\tau_2$, h** | **$\tau_3$, h** | **$\tau_4$, h** | |
| 0.4 | 0.6 | 19.6 | 21.6 | 23.1 | |
| 0.4 | 0.5 | 19.5 | 21.5 | 23.0 | |
| 0.4 | 0.4 | 19.4 | 21.4 | 22.9 | |
| 0.6 | 0.6 | 20.1 | 22.1 | 23.6 | |
| 0.6 | 0.5 | 20.0 | 22.0 | 23.5 | |
| 0.6 | 0.4 | 19.9 | 21.9 | 23.4 | |
| 0.8 | 0.6 | 20.6 | 22.6 | 24.1 | |
| 0.8 | 0.5 | 20.5 | 22.5 | 24.0 | |
| 0.8 | 0.4 | 20.4 | 22.4 | 23.9 | |
| | | **$t_1$ at $\tau_2$** | **$t_4$ at $\tau_2$** | **$t_{avg}$ at $\tau_2$** | |
| 0.4 | 0.6 | 104.6 | 50.8 | 86.5 | |
| 0.4 | 0.5 | 104.6 | 50.8 | 86.5 | |
| 0.4 | 0.4 | 104.6 | 50.6 | 86.5 | |
| 0.6 | 0.6 | 104.6 | 50.3 | 86.3 | |
| 0.6 | 0.5 | 104.6 | 50.2 | 86.3 | |
| 0.6 | 0.4 | 104.6 | 50.1 | 86.3 | |
| 0.8 | 0.6 | 105.5 | 49.7 | 86.1 | |
| 0.8 | 0.5 | 104.5 | 49.8 | 86.2 | |
| 0.8 | 0.4 | 104.5 | 49.8 | 86.2 | |
| | | **$t_1$ at $\tau_4$** | **$t_4$ at $\tau_4$** | **$t_{avg}$ at $\tau_4$** | |
| 0.4 | 0.6 | 90.6 | 61.5 | 81.9 | |
| 0.4 | 0.5 | 90.5 | 61.4 | 81.7 | |
| 0.4 | 0.4 | 90.5 | 61.3 | 81.9 | |
| 0.6 | 0.6 | 90.6 | 60.7 | 81.6 | |
| 0.6 | 0.5 | 90.6 | 60.7 | 81.6 | |
| 0.6 | 0.4 | 90.4 | 60.7 | 81.4 | |
| 0.8 | 0.6 | 90.9 | 60.0 | 81.8 | |
| 0.8 | 0.5 | 91.1 | 59.9 | 81.6 | |
| 0.8 | 0.4 | 90.7 | 60.2 | 81.5 | |
| | | **t$_1$ at $\tau_4$+1h** | **t$_4$ at $\tau_4$+1h** | **t$_1$ at $\tau_4$+2h** | **t$_4$ at $\tau_4$+2h** |
| 0.4 | 0.6 | 75.2 | 64.1 | 58.9 | 66.5 |
| 0.4 | 0.5 | 74.9 | 64.1 | 58.7 | 66.5 |
| 0.4 | 0.4 | 75.2 | 63.9 | 58.9 | 66.3 |
| 0.6 | 0.6 | 75.5 | 63.4 | 59.6 | 65.8 |
| 0.6 | 0.5 | 75.5 | 63.4 | 59.6 | 65.8 |
| 0.6 | 0.4 | 74.8 | 63.3 | 59.5 | 65.7 |
| 0.8 | 0.6 | 76.7 | 62.6 | 60.8 | 65.0 |
| 0.8 | 0.5 | 77.3 | 62.5 | 61.2 | 64.9 |
| 0.8 | 0.4 | 76.1 | 62.8 | 60.4 | 65.2 |

based approaches but in the same time it is advantageous via considerably reduction of the on-line calculations and simplifying the on-line procedures and corresponding hardware and software devices.

From a value point of view the proposed hybrid control system is relatively not expensive; it could be aimlessly incorporated into existing SCADA systems; the functionality of the system is intuitively clear for the operational personnel; the important relation: investment for control/total investment is acceptable; the system possesses robust performance and guarantees safety in all operational conditions.

Table 3. Transient behavior

| **$w$, kg·kg$^{-1}$** | **$\gamma$, -** | **$Q_w$ at $\tau_2$, kWh·m$^{-3}$** | **$Q_a$ at $\tau_2$, kWh·m$^{-3}$** | **$\eta$ at $\tau_2$, %** |
|---|---|---|---|---|
| 0.4 | 0.6 | 49.86 | 71.01 | 70.22 |
| 0.4 | 0.5 | 49.85 | 72.66 | 68.81 |
| 0.4 | 0.4 | 49.82 | 75.07 | 66.36 |
| 0.6 | 0.6 | 62.10 | 86.49 | 71.80 |
| 0.6 | 0.5 | 62.11 | 88.17 | 70.44 |
| 0.6 | 0.4 | 62.10 | 90.62 | 68.53 |
| 0.8 | 0.6 | 74.27 | 101.88 | 72.90 |
| 0.8 | 0.5 | 74.33 | 103.65 | 71.71 |
| 0.8 | 0.4 | 74.35 | 106.14 | 70.05 |

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