Furnace thermal piloting management in siderurgy

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Abstract

In the premium steelmaking industry, the heat treatment of steel products is a key process to obtain the good final physical properties and in a correct range of values. Furnace management requires now improved flexibility and dynamism to ensure the heating quality of the products but bring opportunities for energy savings. One of Vallourec's Industry 4.0 targets is a complete management and control of the production. Furnace "level 2" modelling is one of the keystones for process data generation. Most Level 2 models for furnaces are comparing the real-time simulation results with ideal "static" heating curves to adapt the piloting of the furnace. This method showed great results and robustness over the years but showed a lack of flexibility when a deviation from the ideal production situation occurs. The new generation of Vallourec Level 2 models for billets reheating furnaces, uses another principle and removes the ideal heating curve as an ideal case that rarely happens. Based on the real-time simulation results and the online production data, the computed forecast of the future discharging state of the products allows the software to provide a dynamic prediction of the heating quality with irregular production parameters. For sure these results are obtained with a higher computational cost that was not affordable in the past but is acceptable today with the most recent evolution of information technology, for example, parallelization of the simulations.

Nomenclature

C_{pm}	mass thermal capacity, J.K^{-1}.kg^{-1}	V	volume, m^3
ρ	density, kg.m^{-3}	$F_{1\rightarrow 2}$	form factor between objects 1 and 2
λ	thermal conductivity, W.m$^{-1}\cdot$K^{-1}	K	geometrical element
T	temperature, K	∂K	border of the geometrical element
ε	emissivity	$\boldsymbol{n}$	vector orthogonal to the boundary
σ	Stefan-Boltzmann constant, W.m^{-2}.K^{-4}		

1. Introduction

Applied mathematics and physics are becoming a key competence in the industry of today because the competencies on modelling and especially process modelling are the natural complement of the direct or indirect product measurements. This is also a clear requirement for Industry 4.0 strategies, as a central element in the processes of "digital twin" development. Very often the physical properties of a product can be measured before (A) and after a process (B), but not in between. The knowledge of the products modifications during the travel between states A and B is key information for the quality of the process result: "a", "b" and "c" travels are not giving the same results on the product. The state "B" is a function of travel behaviour.

The simplest way to add information about the process path is to measure; nevertheless, continuous measurement inside a process is often not possible for physical or technical impossibilities (example: it is not possible to measure products temperature by radiative means in a furnace as there is too much disperse radiative atmosphere). One alternative is to simulate online the products physical behaviour, using the existing trustable measurement means (example: the furnace regulation thermocouples); today it is possible to simulate with more and

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more precise tools in terms of code development environments (“Python”, “R” or more classical “C” platforms) and powerful mathematical algorithms ([1], [2]).

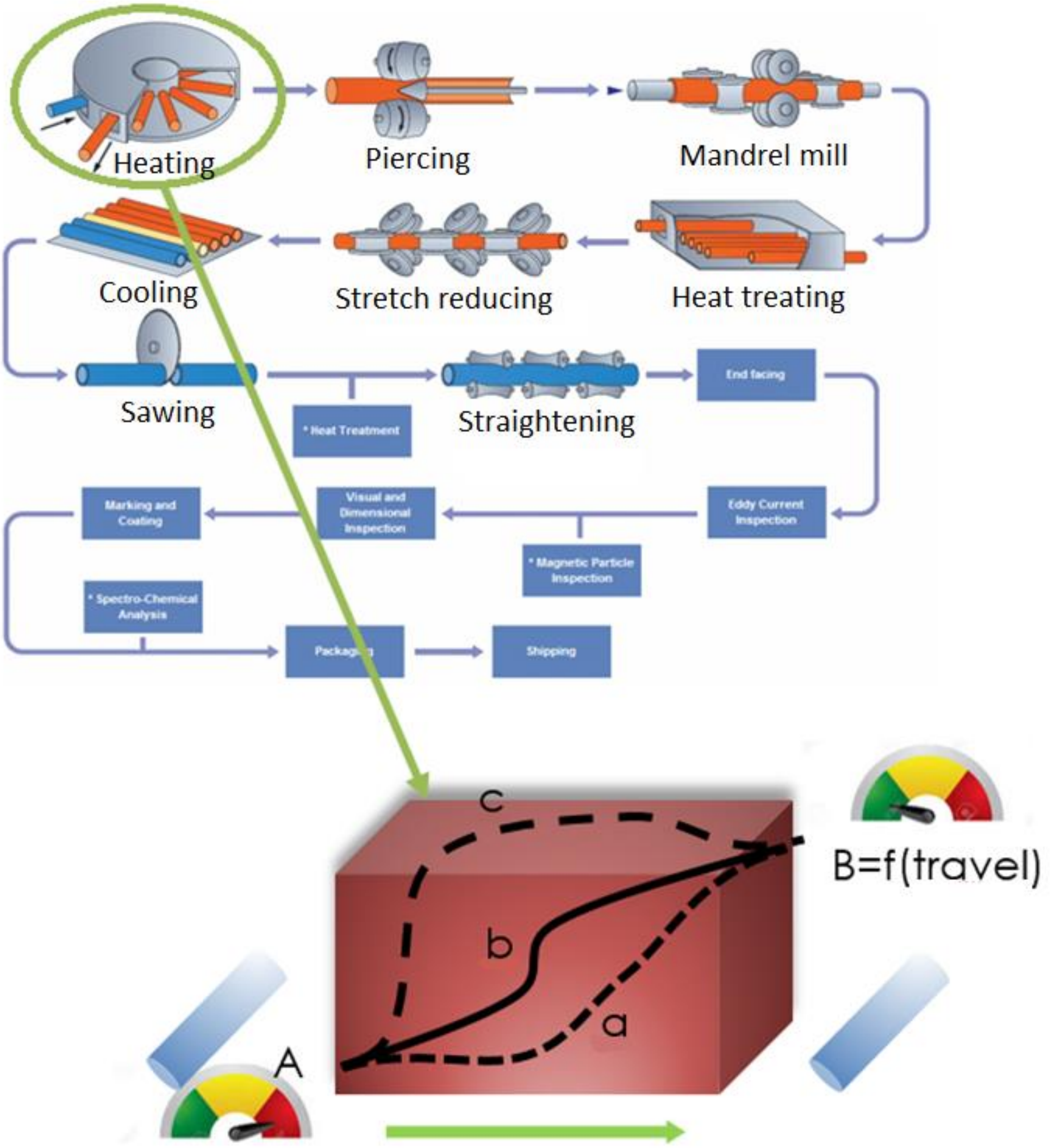

Figure 1: seamless pipes processes production chain and process possibilities in terms of paths in a typical “black box” process

In the siderurgy, the Vallourec field, this discussion can be applied to continuous casting, to rolling, to billet heating, to heat treatment, to cooling processes and so on. In all cases, the process engineer has online “level 1” information on the process itself (such as the furnace temperatures, the pressure on the straightener rolls, the speed of the rolls, the pressure of the smoke) but these information are not directly linked to the steel product under process, and they don’t give clear information on the product.

A “level 2” model that exploits the information of the process elaborating data from production with physical and mathematical knowledge complete and enriches the picture.

In a production line, many sensors are collecting data:

- On the product itself in "*Online*" mode (surface temperature by pyrometer, size measurement…)
- On the product in "*Offline*" mode, extracting samples from production (as quench data, hardness, yield strength, ultimate tensile strength, …)
- On the process itself in "*Online*" model (furnace pressure, furnace temperatures, rolls cooling temperatures,…)

The incoming products are also characterized by specific parameters (dimensions, chemical analysis) collected in Material Tracking System (MTS). These data have a certain precision that is linked to the industrial environment. The reasonable target for a "level 2" process model is to have a precision comparable with the data accuracy.

2. Existing model principles

The level 2 systems commonly used for siderurgy furnaces piloting are designed to pilot the furnace based on an ideal process determined for each dimension and each composition of the product. The ideal heating profile is built to optimize heating quality, productivity, and furnace capacity. A recipe defines the ideal product temperature *for each furnace position* ("heating curve" strategy). It also contains information about furnace and process parameters (zone temperature, cadence…). Every event happening during production, internal or external to the process, can contribute to generate a deviation from the ideal heating curve.

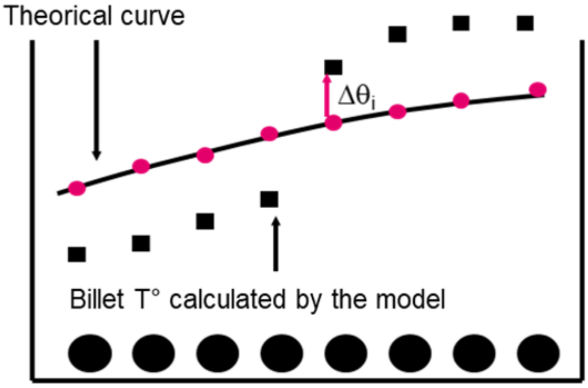

Figure 2: typical "heating curve" strategy description

This family of level 2 systems pilots the furnaces by making comparisons between the "real" products simulated temperature and reference heating curves as shown in *Figure 2*. The furnace setup is modified in real-time based on the results of the comparisons.

As the directly measured temperature of each product is not affordable, the system uses numerical simulation to compute an estimation of the product temperature in real-time. The simulation uses often simplified mathematical path as the *explicit finite-difference method* which provides good enough computational speed and precision.

Such a system ensures the product heating mastery in a standard production environment but its main advantage over manual furnace piloting is the management of non-standard production events (stoppages, cadence variation, heterogeneity of product steel grades and diameter in furnace…). The deployment of this family of level 2 systems in the past for Vallourec furnaces and the optimization of the management of those events reduced the quality issues and gas consumption.

The main drawback of the heating curve is the lack of flexibility at usage. The heating curves management is requiring high maintenance and follows up from process engineers. With new grades and products each year, the number of heating curves to maintain can increase and become tedious. In 2016, a new level 2 system without using any heating curve was developed by Vallourec research teams.

3. New model principles

In the middle of the 2010s, the Vallourec plants had to adapt to new production paradigms with a need to accept in the process quick production changes and the existing level 2 strategy was no more adapted to this environment. Based on that, the research team developed a new generation of level 2, no longer based on the optimal settings (temperature, cadence and so on), but based on the current situation inside the furnace and prediction of discharging state for the whole ongoing products.

Instead of giving information about the billets at each position, the model is fed with the *desired state of the product at the discharging*; some other needs linked to the heating path are also included in the model definition, as rules limiting the heating speed linked to the different steel chemistries to avoid defects.

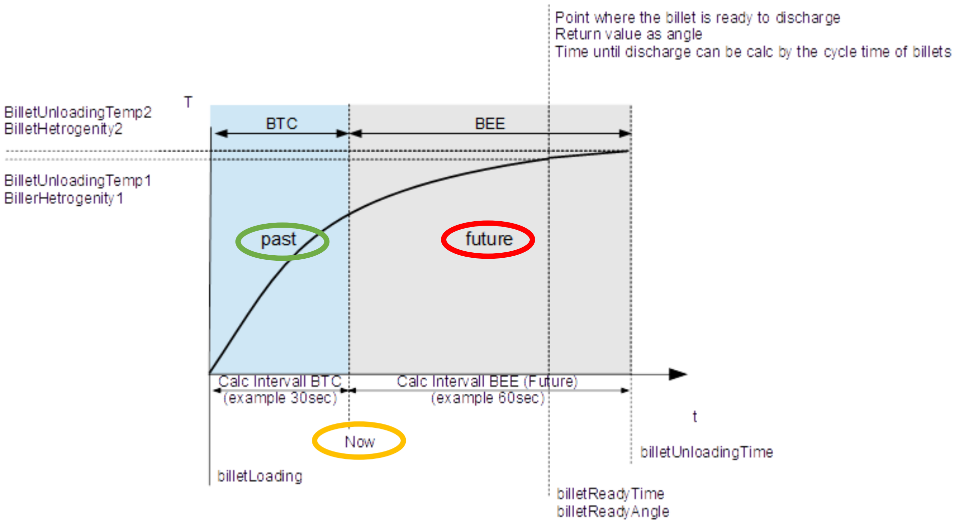

Figure 3: *new model strategy description, to be compared to Figure 2: "past" situation easy to simulate (all the data available, already done in existing strategy), "now" situation (to be simulated in a time shorter than production cadence, already done in existing strategy), "future" state (high computational needs, new requirement for the new strategy)*

The model will simulate the discharging state of all the billets, based on the current production conditions, and will compare it with the desired state. After this comparison, the setpoints inside the furnace will be adjusted to fulfil the desired state.

The other advantage of the new model is an improved stoppage management. A stoppage can be better anticipated and declared inside the model, the forecast of the discharging state will take into account the planned stoppages. This will allow us to pilot with more accuracy, and also to decrease the gas consumption of our furnaces.

This change of paradigm requested also a change in the mathematical model solution; the explicit "good enough" solution was no more able to ensure a sufficient calculation precision. For this reason, the Vallourec research team moved to a more robust implicit scheme.

All these new features required a higher computational power compared to the more traditional strategy and also a robust model to fully trust the forecasted discharging state.

4. Mathematical model

4.1. Heat equation

The billet heating process in a billet heating furnace is modelled by the heat equation associated with boundary conditions given by the Stefan-Boltzmann equation modelling the radiation flows ([3], [4] and [5]):

$$\begin{cases} \rho C_{pm}\frac{\partial T}{\partial t} = div(\lambda \nabla T) & \text{in the domain } \Omega \\ \lambda \nabla T.\mathbf{n} = \sigma \epsilon S F_{ext \to S}(T_{ext}^4 - T^4) & \text{on the part of } \partial\Omega \text{ exposed to radiation} \\ \lambda \nabla T.\mathbf{n} = 0 & \text{on the others parts of } \partial\Omega \\ T(t=0) = T_0 & \text{(initial condition)} \end{cases} \quad (1)$$

The heat equation has an analytical solution in some cases: constant physical properties, simple geometry and boundary conditions. In these cases, the equation is linear. For real industrial processes, the considered equation is not linear because of the coefficients C_{pm}, ρ and λ.

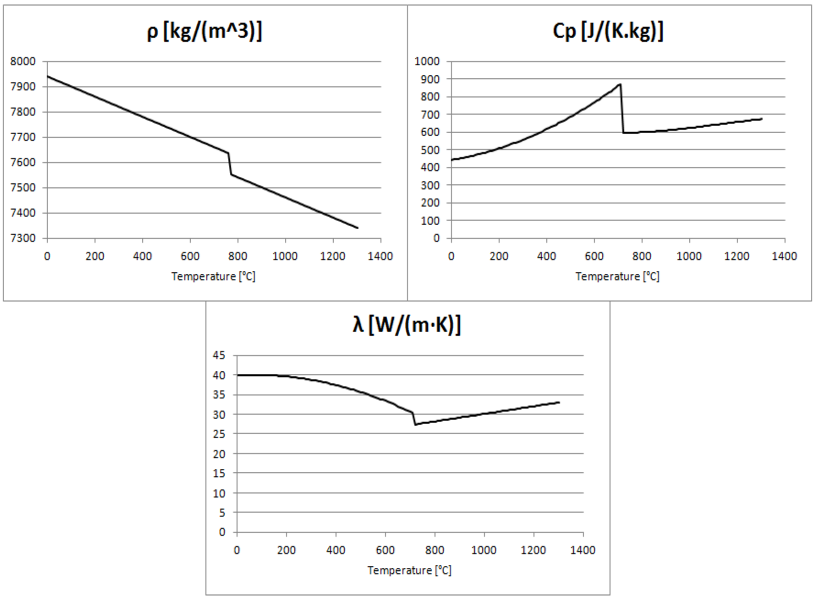

Figure 4: thermophysical properties of a carbon steel

Indeed, the three parameters depend on the temperature. As a function of the temperature, they are not linear and not continuous at the steel transformation points (see Figure 4).

Furthermore, the boundary conditions are not linear with the temperature. The complexity of the problem (1) prevents finding the analytic solution. Then, a numerical solution is required.

The heat equation is then solved in two steps:

- The divergence term is solved with a finite-volume method.
- The time derivative term is solved with a backward Euler finite-difference method.

4.2. Finite volume method

This method is used to numerically solve the spatial part of conservation equations like the heat equation or hyperbolic problems like the transport equation. The method is based on the strong formulation of the equation under an integral form. This formulation avoids the issue of the non-differentiability of the physical properties ([6] and [7]). By integrating the heat equation on every element K of the mesh and with the use of the Stokes theorem on the divergence term, we come to a problem (see equation 2) of flow calculation at the interface $\partial K$of every element K.

$$\rho C_{pm} V_K \frac{\partial T}{\partial t} = \oint_{\partial K} \lambda \nabla T \tag{2}$$

In this method, we can calculate the thermal flow balance of the right-hand side with different methods. For meshes adapted to the geometry, the flow calculation can be done directly by solving the *thermal problem approximated as static*.

For spatial precision, finite-volume methods are linked to the size of the elements and the precision of all approximation methods used for the flow calculations.

Historically, this method was designed by physicists and is built around the thermal balance so the principle of the method remains close to the physical meaning of the heat equation. It is then suitable for improvements by adding a new physical phenomenon to the computation. Indeed, as soon as the thermal flow of a phenomenon can be computed, it can be easily introduced in the model. This point is what makes the finite-volume the better choice for our problem and its industrial purpose. Nevertheless, the finite-volume method does not solve the inherent non-linearity of the complete heat equation [8].

4.3. Euler implicit scheme (or backward Euler scheme)

The equation (1) can be conveniently rewritten under the following form [9]:

$$a(T) \frac{\partial T}{\partial t} = f(T) \tag{3}$$

The purpose of a and f are well-known:

- a is the product ρC_{pm} enriched by the finite-volume spatial discretization. $a(T)$ can be conveniently written as a diagonal matrix if needed and we assume $a(T^{n+1}) = a(T^n)$. This approximation is acceptable but presents issues during the steel transition phase where the thermal properties are discontinuous.
- f is the discrete translation of the space derivative term of the heat equation.

The implicit scheme is given by the relation:

$$a(T^{n+1}) \frac{T^{n+1} - T^n}{\Delta t} = f(T^{n+1}) \tag{4}$$

T^{n+1} is the solution of an equations system. The resolution of the system has a big impact on the computation cost. That is why the implicit scheme is wrongly described as a slow scheme.

The advantage of the backward Euler method and implicit schemes is that there is no CFL condition. Indeed, the scheme offers unconditional stability as there is no theoretical convergence condition. We can choose the time step Δt as big as we want without any convergence issue but only at cost of a loss of precision. This particularity allows simulating long processes with fewer steps than other numerical schemes. For the long run, the implicit scheme offers great performances.

In practice, *f* is not linear and a linear equation system cannot be built. Indeed, we dispose of a non-linear equation system (equation (4)) even if the coefficient **a** can be considered constant over one timestep. We must use an intermediate method to solve this kind of system. We choose Newton's method for its simplicity and its fast convergence [10]. This method is an iterative one and the generalization of the tangential approach methods (see Figure 4). It involves the resolution of multiple non-symmetrical systems of linear equations at each time step which increases largely the amount of required calculations. The implementation of a fast, robust and adapted to sparse system algorithm such as the BicGStab [8] allowed a well-controlled calculation time.

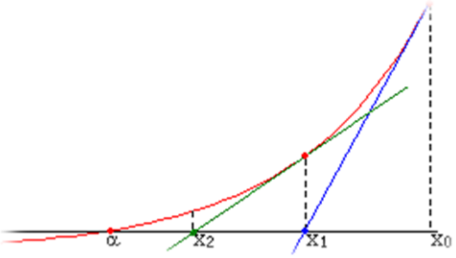

Figure 4 Illustration of Newton's method in one dimension

α is the solution and x_0 the initial guess

5. Billet heating furnace piloting

By using each available process parameter in real-time, level 2 simulates in real-time the whole heating process for each product in the furnace from its current state to its discharging. It allows the evaluation of the current furnace set-up by using the results of the simulation. The product heating quality is estimated by comparing values extracted from the simulation and a few relevant parameters from a piercing and rolling point-of-view such as the average temperature at discharging and the heterogeneity at discharging. The models are validated by comparisons with physical measurements (see Figure 5). Thermocouples are embedded with the product in the furnaces to record the whole process, accordingly with thermocouples measurement errors. Quality criteria allow the evaluation of the comparison and therefore the validation, taking in account a comparison in specific points (thermocouples position corresponding to a specific mesh of the model) and global average of the measurements and the model simulations as in Figure 5.

The large siderurgical furnaces are divided into multiple zones managed independently. Commonly, the first zones are the heating zones where most of the heat is provided and the last zones (soaking zones) are designed to reduce the product heterogeneity. Because of this difference of design, the level 2 system manages differently heating and soaking zones.

For each zone, in real-time, the heating quality estimations of the products currently in the zone are summed up to recommend the zone indexation. Then, based on this recommendation and with regards to furnace and process limitations, plant rules and quality, the level 2 system proposes a new indexation for each zone.

With this piloting principle, the piloting is based on the real-time requirement of the process regardless of the ideal process. As the heating curves are replaced by a few values, the system requires less maintenance. New steel grades and product dimensions are also easier to handle.

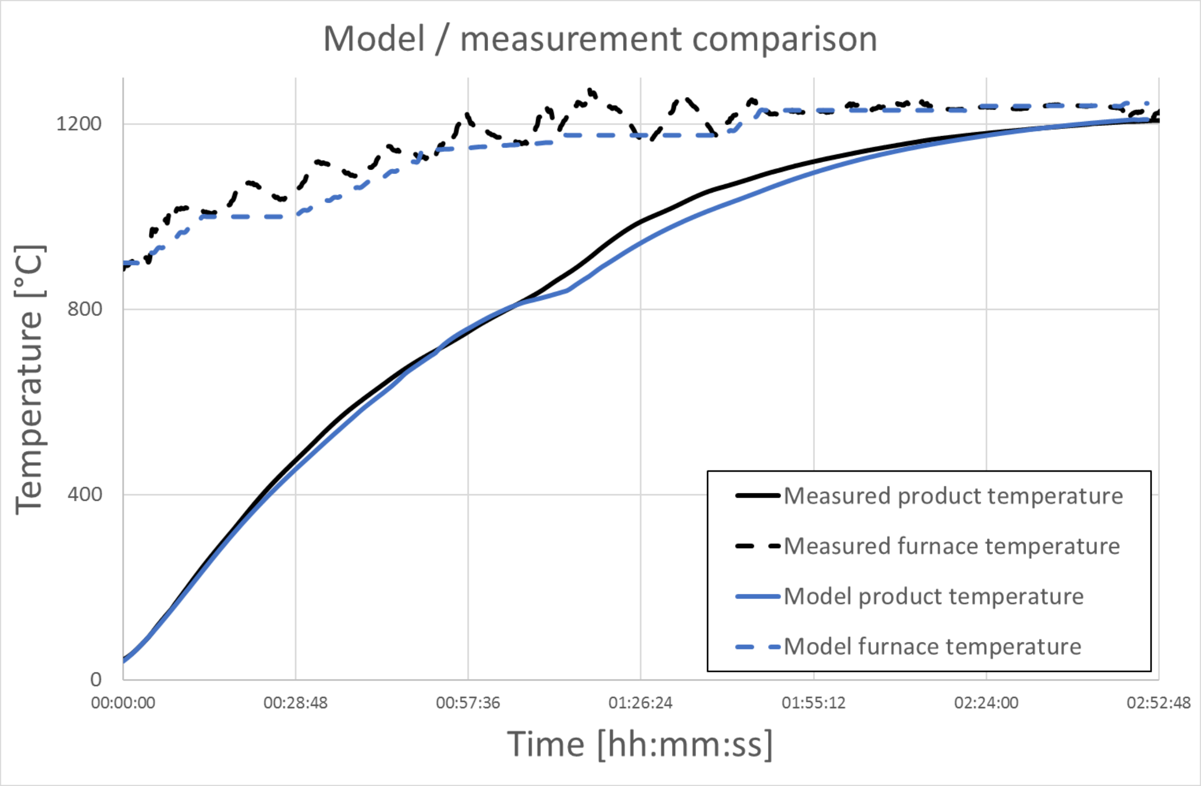

Figure 5 Model and measurement comparison for a billet heating

One important challenge of the principle change relies on the conciliation of the computational cost of the simulation and the real-time furnace management. At each new furnace indexation, one complete simulation must have been performed to ensure the piloting is based on the current process parameter. The computational cost became proportional to the furnace time. For example, for 6 hours of furnace time, compared to the previous level 2 systems, the total simulated time was multiplied by 180. The deployment of the backward Euler scheme described in the previous part (the model is stable even with large time steps) and the development of a parallelization solution allowed the control of our computation time.

6. Conclusion

A new system for furnace management developed inside Vallourec offers great improvements compared to the already existing level 2 systems. The paradigm change compared to the past is a heavier algorithm path that allows the product discharging state prediction; this is possible today with the improvement of servers calculation power that allows a larger amount of calculations but is still compatible with an online production cadence. This system constitutes a powerful tool for production plants regarding product quality mastery and gas consumption. The monthly data analysis from regular production have shown a reduction of 40% of the disparity of product discharging temperature in particular for the larger diameters. The new context of production for the Vallourec group offers opportunities to succeed for flexible solutions in situations of discontinuous production setup. By being highly integrated into modern plants with complete tracking systems and generating a continuously large amount of data of production and forecasts, the new level 2 system is capable to be an actor in the current data analysis revolution with applications in plant management and preventive maintenance.

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