Digital Twin Application for the Temperature and Steam Flow Monitoring of a Food Pasteurization Pilot Plant

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Abstract. In this paper, the development of a Digital Twin of a beverages pasteurization system for temperature monitoring, using NI Lab-VIEW control system toolkit which is composed by a set of probes connected to a cDAQ controller and a user-friendly software interface, developed via G-Code. A cyber-physical production system, composed of a real-time simulation tool and a controller, has been set up and tested on a pilot plant installed in a university laboratory. The paper shows how the software platform, together with the hardware, has been implemented in a traditional system, not (yet) ready for Industry 4.0 technologies, and therefore underlines the main issues occurred during its development. The aim of the Digital Twin is to monitor the machine status, with a particular attention to the temperature reached by the service water and the required steam flow. To demonstrate the effectiveness of this system, a set of simulation and experimental tests has also been carried out.

Keywords: Digital twin, Industry4.0, Temperature Monitoring, Pasteurization System, Food Industry.

1 Introduction

The Industry 4.0 paradigm introduced many key-enable technologies, able to transform a traditional manufacturing process in an advanced cyber-physical production system. Among these, the Digital Twin (DT) appeared as one the most innovative and disruptive tools [1]. The main advantages of DT models encompass the possibility to prevent, anticipate and solve problems relating to the real system in a timely manner, to reduce the time and costs associated with simulations and analyses, to test a process before its implementation and to make effective decisions using data provided in real time [3]. DT is also a key technology of Industry 4.0 for solving safety issues [4]. On the basis of these consideration, a research project has been funded by the Italian national institute for insurance against industrial injuries (INAIL), for developing a DT approach for reducing injuries and hazards in industrial plants. The rationale behind this project stems from an attempt to deepen the current technological evolution of the DT approach, characterized by the use of real time data for modelling an industrial process, with a particular focus of its application in manufacturing processes [2]. This paper describes the first activities of the project, whose aim is to delineate the architecture of

a DT model that will be next used for reproducing the plant functioning in unusual operating conditions, thus allowing for testing the implications for safety and implementing appropriate countermeasures.

The scene of this study is a pilot plant which consists in a pasteurization system equipped with a counter-flow tube-in-tube heat exchanger used for pre-warming the fluid foods (process fluids), through the transfer of heat by water (service fluid), preheated with the steam provided by a heat steam generator. For this kind of plant, traditional control systems are typically used [5], while DT models, which are more user-friendly, are rarely available. This equipment has been already studied in a previous research about the implementation of safety control on fluid pressures [6]. The design phase aims to create a dynamic model of the pilot plant able to simulate the behavior of the machine, monitor its control parameters (in particular, the temperatures), and display the machine status on a user interface.

The scope of this work is therefore to design and validate a DT model built using Labview, for the purpose of monitoring the process water temperature and the steam inlet and solve possible safety issue generated during the pilot plant tests.

2   Digital Twin architecture

A DT dynamic model capable of continuously simulating a beverage pasteurization process and retrieving the parameters of interest has been developed. The pilot plant is equipped with pressure and temperature sensors that provide real data for monitoring the machine status. The developed model consists in a hardware part and a software one. The hardware consists of a set of probes installed on the pilot plant that send the signals via 4-20 mA current loop to a data acquisition system. This latter has been implemented in Labview environment in both simulation and real time acquisition module, using a cDAQ 9133 chassis in which an analogue input module (NI 9208) has been installed. The data acquisition (DAQ) module captures the signal from three temperature sensors (PT100) that measure the inlet temperature of the service fluid and the outlet temperature of the process fluid. These probes have a measurement range of 0°-100°C and transfer the data to the DAQ by means of an analog signal in the range 4-20 mA. The software part was designed via G-code in Labview

2.1   Software and model description

The software part consists of a user interface, called front panel, and a block diagram. The front panel shows the interface by which the user can monitor the system and vary the input parameters. For representing the pilot plant, three additional tabs (panels) were developed, called respectively Model/Controller tab, Machine status tab, and Data Acquisition tab. The block diagram (Fig.1) shows the G-code in which the system equations are written.

The methodology adopted for the development of the DT consists in three distinct steps: (1) development of the simulation model of the pilot plant; (2) acquisition of the real data from the pilot plant; and (3) model validation.

For the development of the simulation model, the following features have been set:

(i) the geometry of the tube in tube heat exchanger consists of six pipes of length equal to 4 meters, with an annular section (diameter 0.076 m) in which the process fluid (hot water) flows, and an internal section (diameter 0.038 m) in which the fluid food flows.

The thickness of both pipes is 3 mm (see [2]); (ii) as far as the output temperature of the fluid food, it is assumed that the product enters the system at ambient temperature (≈25°C) and exits at about 60°C after recirculation; (iii) the flow rate of the service fluid is 12 m3/h; (iv) the outlet pressure of the fluid food from the exchanger has been set approximately at zero (0.005 bar).

Additional assumptions made include the following ones: (i) the outer surface of the exchanger is perfectly insulated. Thus, the thermal power absorbed by the fluid food equals that furnished by the service fluid; (ii) the density and heat exchange values of the water have been set at those at 25°C temperature.

Based on these considerations, a thermodynamic model has been created using Labview as reported in the grey central block of Figure 1.
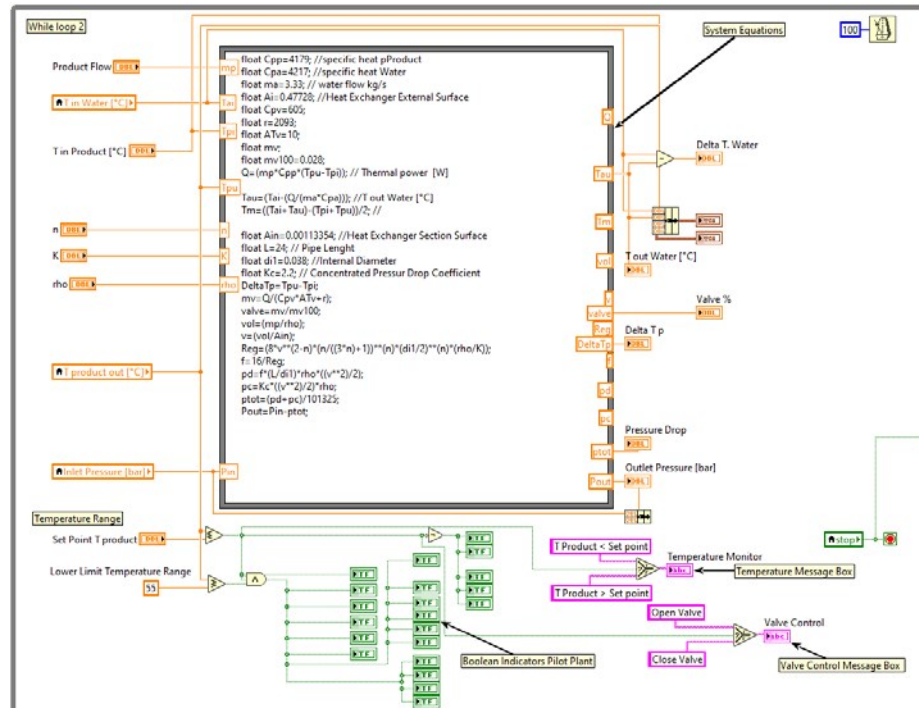
Fig. 1. Block diagram of Labview thermo-dynamic model.

The conceptual design of the DT aims to replicate the behavior of the physical plant taking into account the status of the service and process fluids flowing inside it. After having created the physical model, the first activity is the process simulation by setting some parameters in Labview code and reproducing the signal acquisition by the cDAQ 9133 and the data acquisition 9208 modules. By simulating the signal acquisition from real sensors, the model behavior can be easily evaluated.

The process consists in various steps in which the temperature is simulated as perceived by the PT100 through the cDAQ module, as summarized below:

- Setting of the rheology and heat capacity parameters of the service water and the food fluid;
- Simulating the sensor signal [mA] for to the service water and fluid flow entering the heat exchanger;
- Converting the signal from [mA] to [°C];
- Simulating the sensor signal in [mA] for the pressure at the outlet of the heat exchanger;
- Converting the signal from [mA] to [bar];
- Calculating of the water and food fluid outlet temperature;
- Calculating the pressure of the inlet of the food fluid product.

2.1.1 The Model/Controller tab.

The Model/controller tab (bottom part of Figure 1) shows the model that reproduces the status of the fluids, together with two message boxes: the first one, named Temperature Monitor, shows if the product temperatures meet the set point or not by displaying a message. The second one refers to the modulating intake steam valve, called control valve, and shows the percentage of the requested opening of the valve section for providing the needed steam to reach the desired outlet temperature of the process fluid.

The pilot plant diagram follows a Boolean logic that help visualize the machine status by colors, that change from blue to red; "blue" denotes a normal operating condition of the machine, while "red" indicates an alert status.

2.1.2 The Machine status tab.

The Machine status tab contains the controls and indicators and the graphic representation of the temperature and pressure signals. Based on the hypotheses made for the calculations of the output variable, the system plots the output temperature on a linear graph. An indicator shows the ΔT of the water, which varies according with the variation of the parameters related to the fluid food, and in particular, to the product flow and the inlet/outlet temperatures of the product. The ΔT of the fluid food refers to the range of T of the product and therefore reflects the thermal power exchanged; a variation in this value implies a change in the temperature of the outlet service fluid.

2.1.3 The Data Acquisition tab.

The Data acquisition tab concerns the signal acquisition through the DAQ assistant, or the simulation of the input signals to evaluate the variation of the controlled parameters in a simulated environment, without connecting the system to the physical plant. The tab contains the Start Simulation button that allows switching from the simulation of the data in the software environment, to the real data acquisition thought the cDAQ hardware. The simulation tool also allows creating an analogue signal in current and then reproducing the sensors behavior characterized by a current loop 4-20 mA. The

correct temperature and pressure values can be obtained by means of specific calibrations. Sinusoids made with the DAQ assistant are displayed within the waveform chart, while the sampling frequency and the samples per cycle represent input data that the operator can change according with the level of accuracy and number of data required when simulating different cases. The data about the inlet temperature of the service fluid and about the inlet and outlet temperature and pressure of the process fluid can be displayed by simulating the process.

3 Simulation tests

According to [7], simulation is an effective tool to be used for investigating the behavior of a system anytime it cannot be immediately observed or reproduced in practice. For the plant under examination, this is exactly the case. Indeed, the plant can be observed in its normal operating conditions (which will be detailed in the experimental tests), but obviously, it cannot work outside its normal operating conditions without jeopardizing its safety or the safety of people working on the plant. For reproducing these anomalous situations, simulation was used.

3.1 Initial setting

The first aspect investigated is the variation in the water temperature during the heat exchange phase. To evaluate the temperature reached by the water, the thermal power exchanged within the process fluid and the service one was assumed to vary according with the heat capacity, the flow and the ΔT between the inlet and the outlet of the heat exchanger. The system acquires the input parameters and calculate the outlet temperature of the water at each variation of the input. The evaluation of the needed thermal power can also be useful to calculate the required flow of steam at the inlet. For the evaluation of the intake valve's opening percentage, it was assumed that the maximum steam value provided is 100 kg/h, according to the real capacity of the installed electric steam generator; this corresponds to about 0.0277 kg/s, which represents the input parameter defined as mv100 in the G-code developed. The ratio between the steam flow evaluated using the thermal heat equation and the mv100 value represents the intake valve's opening percentage. During the testing phase in the simulation environment, the input parameter was simulated as a continuous signal that fluctuates between the real operating conditions, as shown in Table 1. For the remaining input parameters, steady conditions were instead assumed; in particular: the inlet product temperature was set at 50°C; the product flow was set at 0.4 kg/s; the set point of the product temperature was set at 60°C.

Table 1. Initial setting of the simulation test.

	T max[°C]	T min [°C]	Sample Rate [Hz]
Inlet Water Temperature	100	90	0.33
Outlet Product Temperature	60	55	0.33

3.2 Results with simulated data

The system provides three different outcomes based on the assumptions made. A first result can be seen in the message box, which shows whether the product temperature is higher (>) or lower (<) than the set point. As second outcome, the machine status monitor displays the tube-in-tube part of the pilot plant in blue color if the product temperature is in a range between the lower limit (55°C) and the set point, or in the red one if the set point is overcome. For the valve control, a message box displays the intake valve status (valve opened vs. valve closed), while a numeric indicator shows the percentage of opening required for the valve to match the steam flow needed to reach the desired output temperature of the water. An example of the results obtained is shown in Figure 2, referring to the case in which the set point of the product temperature is overcome.

   As shown in that figure, the system requires the valve to be opened by about 40% to meet the set point; the temperature monitor displays the correct message, and the Boolean indicators turn red as expected. In the opposite situation, i.e., if a small temperature gap is observed between the inlet and outlet of the product, the percentage of valve's opening (and therefore the steam flow required) would instead be low. To evaluate the system's response in out-of-range cases, a test has been run by varying the product temperature, with a simulated signal temperature higher than the set point and one lower than the minimum threshold.
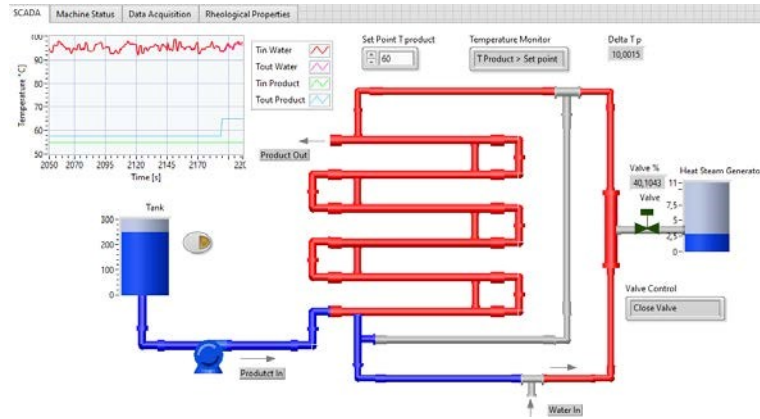

Fig. 2. System status when the fluid product temperature set point is overcome.

4 Experimental tests

To assess the software robustness and validate the system model, a testing phase was carried out in laboratory settings. The signals of the three input parameters were acquired on the physical plant through the cDAQ hardware. The sample rate adopted was 0.33 Hz and the number of samples for each run was set at 1. The parameters assumed in the steady state conditions are the inlet product temperature (52°C), the product flow (0.4 kg/s) and the set point of the product temperature (60°C). The main outcomes are related to the behavior of the system in real environments. As shown in Figure 3, the

input signals acquired show a "T_in Water" of 91.25°C and a "T_out product" of 57.10°C. With the data acquired and the initial setting, the Temperature Monitor (Figure 4) shows the correct message, and the machine status is displayed in blue. The ΔTp indicator led to a valve opening of about 38.87% while the valve control state displays the Open Valve status, required to reach the set point.
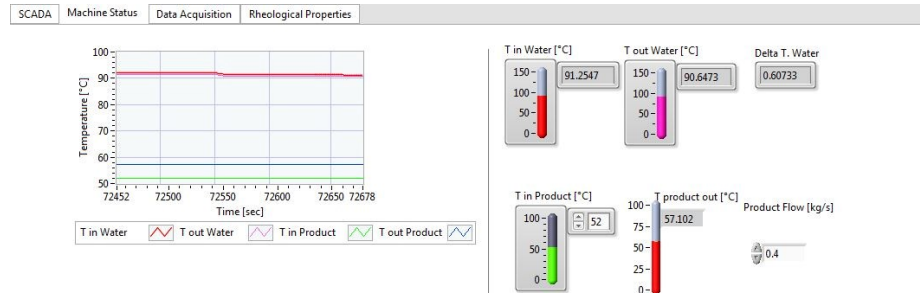

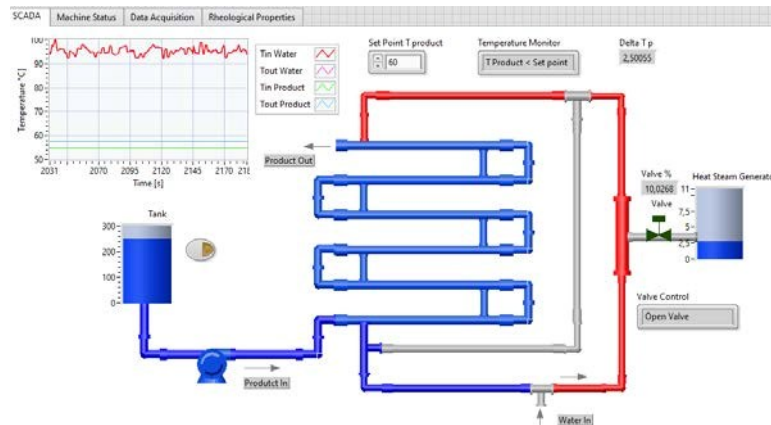**Fig. 3.** Real data acquired by the system (T_in water, T_out product).

Fig. 4. DT model with the acquisition of real signals from the field.

5   Conclusions and future research

The present paper aimed at developing and testing a DT application for monitoring the temperature of the service fluid flowing in a real plant and the amount of steam needed for its heating. The model has been implemented in a Labview environment; tests carried out both in simulation and laboratory environments, showed that the model reproduces the system functioning with good precision. Compared to traditional control systems, the proposed DT model is more user-friendly and can be easily learnt in its functioning by any employee working on the plant, which is expected to encourage its prac-

tical usage. Moreover, its future link with safety issues, mentioned earlier in the manuscript, will represent an innovative approach for reducing injuries and hazards in industrial plants. Starting from this study, future research activities will introduce additional features of the control system, by acting on the PLC when some parameters exceed the safety condition (e.g., excessive water temperature or pressure). From a more practical point of view, it is planned to complement this study by installing an internet connection in the laboratory environment, for real time monitoring of the plant by the employees.

Acknowledgements

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