Modelling experiments with small-scale thermal system used for pig fattener heating

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Abstract. This study presents the ongoing research conducted in the field of thermal systems which are commonly used in agriculture and also in other fields to utilize the solar thermal energy. This paper describes a small-scale physical system that is controlled by hardware-in-the-loop (HIL) method. The solar thermal input is realized by a heating element, which can provide a 60 W power in total. The input energy is controllable via Pulse Width Modulation (PWM) to mimic the stochastic changes in weather. The heat storage unit is a 1 litre volume isolated tank, which contains also the heat exchanger unit. The working fluid in this system is water which is forced by custom made peristaltic pumps both on the “collector” side and on the output. In this way the mass flow rate of the pump can be controlled on the heat exchanger and on the user side, as well. The user side is modelled by a water-air heat exchanger forcing cooled air by a varying speed fan. The temperatures are measured on several points of the system which are used to control the flow rates. Experiments were performed with various controlling algorithms in order to find an optimal solution to provide heat for a pig fattener. The recent status of the test results is shown in the case of On-Off and PID control methods in contrary.

1. Introduction
In this section, the literature overview of the topic will be presented with discussing the studied topic actuality and the issues of the use of solar energy resources.

1.1. Actuality of the topic to be studied
Nowadays - because of the overpopulation of world - it is too pressing to permit a longer delay [1] mitigating food crisis. More than 1.9 billion people exists on the Globe of 6.7 billion who are suffering of malnutrition. The number of people existing near to critical starvation exceeds 600 million [2].

As a scenario the population of the World could reach 9.6 billion inhabitants by the time 2050. This increase requires to enlarge the food production by 70 % [3] and still we will be able to keep only the present condition.

Besides, we are in a shortage of food in the World we have less and less area where we could produce that [4].

So, the biggest challenge is the growing demand from population growth [5] and climate change [6].

The better utilization of arable land and energy seems to be a good solution.
In our current society, it is customary, and even expected, to get cheap, high-quality meat every day, so it is important to produce it quickly and at low cost with large commercial conditions. The use of renewable, especially solar energies in livestock farming should lower the production costs, which could result in a more affordable food source. Pig meat is one of the most selling animal protein sources in Europe. Because pigs are highly sensitive to environmental parameters such as air quality and above all to temperature [7], it is important to know what production parameters and technologies are needed for the most efficient production. Therefore, a small-scale physical system was implemented that is controlled by hardware-in-the-loop (HIL) method. This method gives the possibility to compare various controlling algorithms to find an optimal solution to keep the thermal parameters of a pig barn optimal.

1.2. Solar energy issues
The development of the solar systems is highly speeded up in the recent years. For that reason, a lot of experiments were carried out and a lot of prototype systems were built. Generally saying, it is expensive to build a physical system to do experiments. With the aid of the computer-aided modelling methods these costs can be reasonably reduced, in spite of that such algorithms were created for a specific task and they not provide too much flexibility. The model-based design is a possible way to resolve this issue [8] This designing method uses mathematical models and the simulation of them to reduce the cost and to speed up the test phase [9]. This approach is useful to analyse and develop an existing solution, as well [10].

The extension of the model-based design is the hardware-in-the-loop (HIL) simulation, where real-time data is used for the model, this is achieved by using embedded systems and sensors. The “hardware” part can be either FPGA devices or more common embedded systems, such as Arduino or Raspberry Pi [11]. There are two main approaches to make a HIL simulation, one where the simulation runs on a host machine and the embedded system acts like an input. In this way, a complex simulation can be built, without the hardware limitations of the embedded system. The other method is where the whole simulation runs on the embedded system, this way the system becomes portable, but it requires more advanced hardware [12].

The presented simulations were performed using a custom-made Simulink library called SimSolar software, which provides a block-oriented modelling environment [13].

2. Materials and methods
In the following section the used devices and models will be presented.

2.1. Physical layout
First, a small-scale physical model of a solar collector unit was created, which has to be controlled accurately. For this reason, an electric heater unit was used to be able to precisely dose the energy which is representing the solar thermal energy input. The model was made so, that there will be a room for further improvements, which are either pre-planned or needed based on the data of the tests. In this experiment only the temperatures on the input of the collector, on the output of the collector and the temperature of the heat storage tank were measured.

The model utilizes 8 DS18B20 digital temperature-sensors, three in the heat storage unit, one in the collector unit, on both collector in and out measurement points, one on the user output, which is the water-air heat exchanger and one ambient temperature measurement point.

Figure 2 shows the block diagram of the experimental device assembly while figure 3 shows the actual experimental system. Two FDM (Fused Deposition Modelling) printed peristaltic pumps were used, to vary the flow rate in both collector, and user loop.

Since peristaltic pumps are operating on the principle of positive displacement, therefore they can be used to precisely control the flow rates with the use of stepper motors as a driving solution. To drive the stepper motors, A4988 stepper driver-boards were applied.
As a heat storage unit, a polypropylene plastic bucket insulated by roof insulation material is used, with a built-in a brass coil, which is used to exchange heat between the storage and collector loop.

First, we measured a heating cycle. We used 50W in average to heat the collector circuit, and we drove the pump of the collector circuit at 300 l/min., which translates to approx. 0.08 l/min flowrate. In this experiment we used all the sensors. Figure 1 shows the results of this test.

The user pump wasn’t applied in this test.
The power is provided by a RIGOL DP832 three channel linear lab bench power supply (Figure 4). This supply made possible to constantly monitor the used energy to power the heating element. Since it is a variable supply, the output power can easily be varied.

2.2 Arduino firmware

The program running on the Arduino (firmware) controls the stepper motors of the pumps, collects the temperature readings of the sensors and handles the communication with the Simulink system as it is shown in figure 5. The data of the sensors is read by a 10-bit analogue-digital converter and sent to Arduino board via one-wire communication. The Arduino then sends the data array to the Simulink model, where the raw-data-temperature conversion happens.

The communication is a standard full duplex serial communication (RS232) with a baud rate of 9600 running form an interrupt routine, this way the control of the stepper motors is mostly uninterrupted. This solution was necessary in order to provide the reliable speed of the motors.
2.3 On-Off controller process

The HIL solution was first used in an On-Off controlled process which can be seen in figure 6.

The model contains the necessary components of the serial communication (configuration, read, write), the logic of the communication, the temperature converting routines and the On-Off controller unit itself.

![Simulink model of the On-Off controlled system](image)

**Figure 6.** Simulink model of the On-Off controlled system

The data of the signals of the communication build from byte strings packed from 2 bytes, which is the standard ‘uint16’ format (16 bits), but the blocks of the mathematical computations uses double precision floating point types, which are ‘doubles’, so the necessary conversions had to be made.

The readings of the temperatures contain some noise, so a simple Finite Impulse Response filter was used in order to compensate this effect, this solution can be interpreted as a moving average.

The control logic of the HIL simulation contains 4 steps, as it is shown in figure 7:

1. **Initialization**, 2 - get the temperature of the storage, 3 - set the speed of the motor, 4 - go to step 2

![Communication logic](image)

**Figure 7.** Communication logic
To achieve the stable operation a special toolbox was used: Stateflow. The Simulink environment has no built-in solution for a so called, ‘state machine’, but this type of communication requires one. The state machine is a simple system, where the operation of the machine depends only on the internal state of the system, like a Turing machine. The Stateflow toolbox enables this approach.

The chosen controller was an On-Off controller, which has a binary controlling algorithm, because there are only two possible outputs, usually a low (0) and a high (1) level signal, the actual value of the ‘high’ and the ‘low’ signals depends on the application. The hysteresis prevents the controller for the rapid oscillations. With the introduction of the error function, which can be written as:

$$\varepsilon(\tau) = r(\tau) - y(\tau).$$  \hspace{1cm} (1)

The operation of the controller can be described as follows:

$$u(\tau) = \begin{cases} 1, & s = 1 \\ 0, & s = 0 \end{cases}$$ \hspace{1cm} (2)

where $s$ is the internal state of the controller, it depends on the previous state as follows:

$$s_\tau = \begin{cases} 1, & \text{if } s = 0 \text{ & } \varepsilon(\tau) < -h/2 \\ 0, & \text{if } s = 1 \text{ & } \varepsilon(\tau) > h/2 \\ s_{\tau-1}, & \text{otherwise} \end{cases}$$ \hspace{1cm} (3)

The controlled parameter in this case is the flowrate of the pump on the user side. The flowrate can be controlled by the rotational speed of the motor as the following.

$$Q = V_g n.$$ \hspace{1cm} (4)

2.4 PID controller

The PID (Proportional–Integral–Derivative) controller was the second trial to be implemented. The PID is a more sophisticated, continuous controlling algorithm. The governing equation of the PID controller:

$$u(\tau) = P \varepsilon(\tau) + I \int_0^\tau \varepsilon(t) \, dt + D \frac{d}{dt} \varepsilon(\tau)$$ \hspace{1cm} (5)

Figure 8. Simulink model of the PID controlled system
The base of the HIL system is the same, only the controller has changed as seen in figure 8. This is one of the main advantages of the block-oriented modelling design, that the change of the whole models means only the replacement of some of its blocks.

3. Results and discussion
The figures 8-11 show the results of the simulation trials. The temperature of the storage (blue), the temperature of the collector input (red), the temperature of the collector output (orange) and the setpoint can be seen in figure 9 in case of the On-Off controller. Figure 10 shows the output of the On-Off controller.

The temperatures, with the same colouring, of the PID model are in figure 11 and the output of the PID controller is in figure 12.

![Figure 9. Temperatures in the function of time (On-Off)](image)

![Figure 10. Control signal (On-Off)](image)

![Figure 11. Temperatures in the function of time (PID)](image)

![Figure 12. Control signal (PID)](image)

4. Conclusion
In conclusion, it can be stated, that these applications have a very large time constant, so they are hard to control. In our cases the experiments showed, that PID controller can be very unstable when controlling the temperature of the heat storage unit. This is due the inaccurate measurement of the temperatures. So, the first improvement will be to use a sophisticated temperature measurement device to acquire data from the system. The PID method, in addition, is very sensitive to the working point. It means that when the P, I and D parameters of the controller are tuned, and so the system gets into another setpoint or different starting conditions, the control can drastically overshoot. The On-Off controller, in this case, was a better solution then the PID. In conducting further experiments, more algorithms will be tested. It is assumed, that due to the large time constant of the system the model-based control would be the optimal solution.
Nomenclature

| Symbol | Description |
|--------|-------------|
| $D$    | coefficient of the derivative member |
| $h$    | hysteresis |
| $I$    | coefficient of the integral member |
| $n$    | rotational speed of the motor, $l/s$ |
| $P$    | coefficient of the proportional member |
| $Q$    | flowrate, $m^3/s$ |
| $r$    | reference signal |
| $s$    | state of the controller |
| $u$    | control signal |
| $V_g$  | geometric volume, $m^3$ |
| $y$    | output of the system |
| $\varepsilon$ | error |
| $\tau$ | time, $s$ |

References

[1] Glaeser B 1989 *Umweltpolitik zwischen Reparatur und Vorbeugung. Eine Einführung am Beispiel Bundesrepublik im internationalen Kontext* Westdeutscher Verlag GmbH Oplade pp.14-15

[2] Szakály S 2004 *Táplálkozási dilemmák és az élelmiszerek fejlesztésének világstratégiai irányai* Élelmiszer Táplálkozás és Marketing, évf. 1 sz.: 1-2

[3] Northoff E 2016 *2050 A third more mouths to feed* Food and Agriculture Organization of the United Nations

[4] EEA Report. 2006 *Urban sprawl in Europe, The ignored challenge* European Environment Agency Report No 10 ISSN 1725-9177

[5] Boserup E 2017 *The conditions of agricultural growth: The economics of agrarian change under population pressure* Routledge pp.4-7

[6] Zhang P, Zhang J and Chen M 2017 *Economic impacts of climate change on agriculture: The importance of additional climatic variables other than temperature and precipitation* Journal of Environmental Economics and Management 83 pp.8-31.

[7] Cross A J, Keel B N, Brown-Brandl T M, Cassady J P and Rohrer G A 2018 *Genome-wide association of changes in swine feeding behaviour due to heat stress* Genetics Selection Evolution 50 p.1

[8] Paterno F 2012 *Model-based design and evaluation of interactive applications* ISBN: 978-1-447-10445-2

[9] Erdélyi V and Jánosi L 2017 *Digital twin and shadow in smart pork fettiners*, Proceedings of the 5th International Scientific Conference on Advances in Mechanical Engineering Debrecen Hungary ISBN 978-963-304-1 pp.142-146

[10] Bílčík M, Božíková M, Petrović A, Malinek M, Cviklovič V, Olejár M and Ardonová V 2018 *Analysis of selected photovoltaic panels operating parameters as a function of partial shading and intensity of reflected radiation* Acta Technologica Agriculturae Vol. 21 pp.14-17.

[11] Velasquez D R, Collazos VT and Mines J M 2017 *A low-cost hardware-in-the-loop real time simulation of control systems* Proceedings of the 2017 IEEE 24th International Congress on Electronics Electrical Engineering and Computing INTERCON 2017 ISBN 978-150906362-8

[12] Ilyas A, Ayyub M, Khan MR, Jain A and Husain M 2018 *Realisation of incremental conductance the MPPT algorithm for a solar photovoltaic system* International Journal of Ambient Energy Volume 39 Issue 8 ISSN 0143-0750 pp.873-884

[13] Tóth J and Farkas I 2017 *Developing a Simulink library for solar energy applications* R&D in Mechanical Engineering Letters Gödöllő Hungary Vol. 16 HU ISSN 2060-3789 pp.89-95