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Design and implementation of a self-cleaning heat exchanger using a digital twin

Sam Brooks[a]*, Ayman Yasin[a], Kazeem Alatishe[a], Rajkumar Roy[a]

aSchool of Mathmatics, Computer Science and Engineering, City, University of London, Clerkenwell, London, EC1V 0HB
* Corresponding author. Tel.: +447958136759; *E-mail address:* sam.brooks@city.ac.uk

Abstract

Fouling can be reduced by careful design or surface treatment; however, regular manual cleaning is often still required. In this study, a self-cleaning heat exchanger system to automatically identify and remove fouling was designed. The Self-cleaning system was designed to operate automatically without human input and use a backwash of water through the heat exchanger tubes to clean them. A digital twin (DT) is utilised with a model of the performance of the heat exchanger; this is the first known research where a DT is used to control a self-cleaning (or self-engineering) response. The steps used to develop the DT are described, and the logic used to determine when to trigger self-cleaning. Temperature readings are compared to the DT model to determine when heat transfer is impeded by fouling. Tests performed with fouling added successful demonstrated the DT and self-cleaning. The effectiveness of the heat exchanger before fouling, with fouling and after cleaning was used to determine the effectiveness of the self-cleaning. The original performance returned by cleaning varied with 15%, 81% and 52% returned in each experiment.

Keywords: Self-engineering; digital twin; self-cleaning; through-life engineering services

1. Introductions

Self-engineering (SE) systems have a built in ability to identify any loss or potential loss of function and then automatically restore the functionality to maintain its availability and improve system resilience [1]. SE aims to reduce the maintenance and prolong the life of a system making it especially useful in servitisation businesses. Previous research by Brooks and Roy has focused on reviewing existing SE systems in engineering and biology [2]. Examples of SE responses include self-healing, self-repair, self-reconfiguring, self-adapting and self-sealing. This work focuses on a self-cleaning (SC) based SE response and demonstrates the development of a SC heat exchanger (HX) and the Digital Twin (DT) used during operation.

Nomenclature

c_p	Specific heat capacity [J °C $^{-1}$ kg^{-1}]
C	$c_p \dot{m}$ [W °C $^{-1}$]
ε	Heat exchanger effectiveness [-]
$\dot{m}$	Mass flow rate [kg s^{-}]
Q	Estimated total heat transfer [kJ]
T_{Cin}	Cold inlet temperature [°C]
T_{Hin}	Hot inlet temperature [°C]
T_{Hout}	Hot outlet temperature [°C]
UA	Overall heat transfer coefficient [W °C $^{-1}$]

1.1. Self-cleaning heat exchanger

SC is predominantly used to describe hydrophobic (often bioinspired) materials; this is an example of robust design but not SE as the hydrophobic surface causes continuous water and material removal. A SE SC response refers to systems that can automatically identify fouling and take action to remove it when needed. Examples include SC filters [3] which register fouling using pressure drop and automatically use a backflow of water [4] or pulsed water jets [5] to clean fouling.

There are many different types of fouling within HX, including particulate, precipitant or biological; fouling impedes heat transfer, reducing the processing capacity and increasing operating costs. Cleaning often requires plant shut down to allow disassembly of the HX. Automated online cleaning methods have been developed using backflow of water, ultrasonic pulses and foam balls added to the flow [6]; however, these still need to be initiated by a human operator. Another alternative is fluidized bed HXs, which use small particles to erode fouling [7]; this is only suitable for certain applications, and particulates can damage the HX and other components over time. There is a need for a fully automated SC HX which registers fouling building

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up and takes action to restore the HX to its original condition. The aim of the research was to design and create a SC HX with a DT. This research presents the first fully autonomous SC system with a built in DT.

1.2. Digital Twin

A Digital Twin (DT) consists of three key parts: a) physical system in the real world, b) virtual representation of the system, and c) connection of information and data between the virtual and physical system [8]. DTs have been used in many different industries, including manufacturing, smart cities and health care [9]. Various researchers have presented step by step guidelines [10] or frameworks [11] for digital twin development

There are a few examples of DT developed for HXs; Bottani et al. [12], developed a DT for a drink pasteurization process on lab view [12]. It was designed to provide live feedback to the operator about system performance and anomalies which could cause safety problems. However, it has not yet been implemented in a physical set up. Hammarström [13] designed and tested a DT for a ship engine cooling system. The research focused on the integration of sensor data into the model and did not get the DT working fully and optimising the HX performance. Min et al. [14] focused on using machine learning techniques to predict loss of performance in a petrochemical plant. Previous operation data was used to train the DT to recognise potential losses of performance and adjust operation.

All three examples currently rely on user intervention to change the performance of the system, there is no fully autonomous decision taken by the DT. In this research, a SE DT is created that can autonomously respond to a loss of function without user input and aims to reduce the cleaning servicing required. An automated cleaning mechanism could involve only automating the cleaning response. A SE SC system is different because it is a complete built in full automated monitoring and response system.

1.3. Paper structure

Section 2 outlines the SC HX test rig utilised in the experiment. Section 3 discusses the development of the DT. Section 4 shows results taken from the DT with the SC function initiated. Finally, section 5 is the discussion, conclusion and future work for the study.

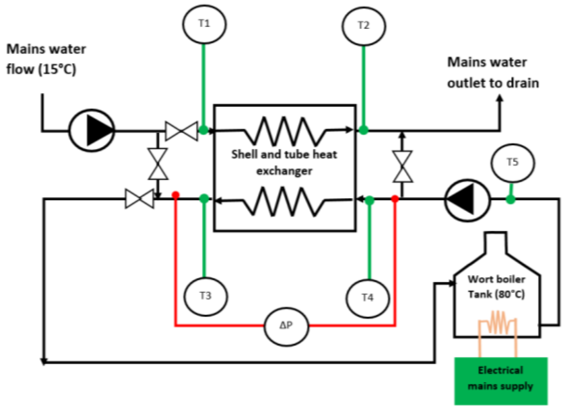

Fig. 1 – Diagram of SC HX experimental test rig with a shell and tube HX. Green lines show temperature sensors, red shows pressure sensors

2. Self-cleaning test rig

2.1. Test rig set up

A diagram of the SC HX can be seen in Fig. 1 and a picture of the test rig in Fig. 2. The HX used was a Bowman EC120 shell and tube HX with stainless steel pipes. A water boiler is used to provide hot fluid at 70 to 80ºC, while mains water (At 20°C) is used as the cooling fluid. Automated motorized valves controlled by relays and an Arduino Mega control the fluid flow in the HX. A differential pressure sensor (MP3V5010DP by NXP) and a Hall Effect flow rate sensors feed data into the Arduino. Temperature data is provided by thermocouples using a TC-08 Pico logger. Sensor data and valve control are managed by the DT run on Simulink; see section 3 and Fig. 2 for more details. The HX is set up in a counter-current arrangement with hot fluid in the inner tubes and cold in the shell.

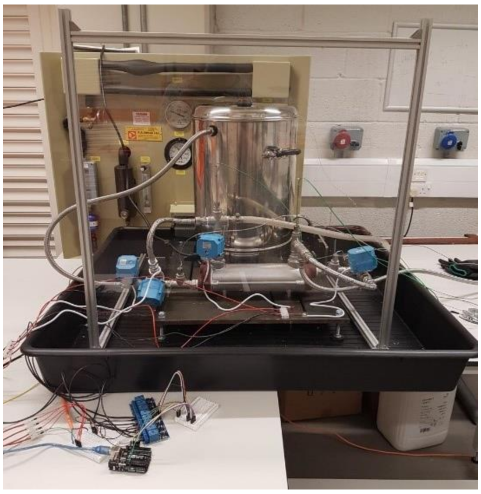

Fig. 2 – Photo of SC HX test rig used.

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2.2. Operation and fouling

The fluid cooled in the HX is a mixture of malt extract syrup and water (also known as wort) used in brewing as a base for beer. The experimental set-up was designed to replicate the process of cooling the wort mixture; however, the HX outlet was added back to the inlet tank and reheated to allow the experiment to be run for extended periods.

Fouling in HX builds up over months of operation. To reliably demonstrate the SC process in operation, fouling was added at a set point during experiments. Fouling was added in the form of malt extract syrup. The syrup was poured into tubes of the HX then heated using a hair dryer to help it spread and adhere to the HX sides. The resulting fouling caused a drop in heat transfer which was registered as a drop in HX effectiveness (ε). HX effectiveness is defined in Equation 1, where C corresponds to the product of specific heat capacity (c_p) and mass flow rate ($\dot{m}$) for hot (C_h) or cold fluid (C_c); C_{min} is the minimum of C_h and C_c.

$$\epsilon = \frac{C_h(T_{H,in}-T_{H,out})}{C_{min}\,(T_{H,in}-T_{C,in})} \qquad (1)$$

2.3. . Self-cleaning mechanism

For this test rig a faster backflow of water was used to remove the fouling deposits. This was provided by switching the valves used in the set-up to allow the inlet cooling water to flow from the outer shell side to the inner tube side.

3. Self-engineering digital twin set-up

The development process of the DT has been outlined under the eight steps used in [10]: requirements, information flow, virtual representation, data exchange, analysis, actions and validation.

3.1. Step 1 - Requirements

Key requirements and constraints of the DT are outlined in Table 1.

Table 1 – Requirements and constraints of the DT for SC HX.

Requirements	Constraints
• Operate and monitor the HX autonomously • Manage and control the cleaning process • Record and store data and utilise to improve the DT performance	• Sensor accuracy sufficient to register fouling reliably • The DT and models used should operate in real-time

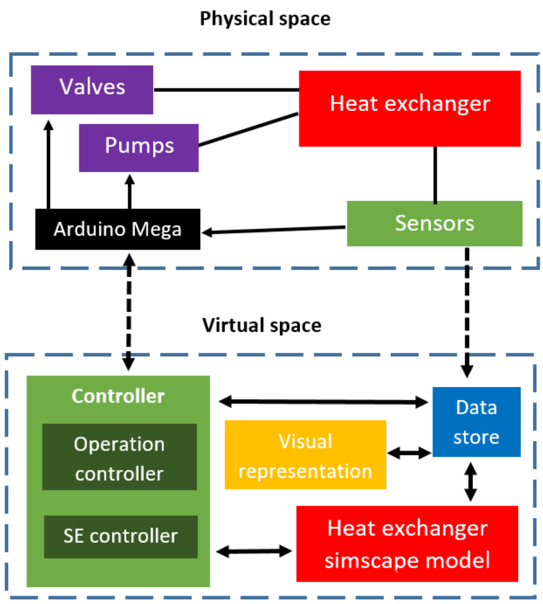

Fig. 3 – Diagram showing the different virtual and physical components and how information is transferred.

3.2. Step 2 – Information flow

Sensors feed data into the DT built on Simulink. Temperature data is fed directly via a serial USB connection while pressure and flow rate are transferred via an Arduino serial connection to the computer running Simulink. Historical data from previous clean HX tests are stored in a separate file which can be accessed if needed. The Simulink model contains four key parts a controller (with a self-engineering and normal operation part), a virtual simulation of the HX, a visual model, and a data storage and processing block. Fig. 3 shows a diagram of the information flow between the virtual and physical space.

3.3. Step 3 – Virtual representation

The virtual representation of the system in shown on the Simulink model which displays live data to the user and indicates when the SC operation has been initiated. Fig 4 shows a picture of the virtual Simulink model, including the virtual representation. Simulink's capabilities limit the user interface, but a basic interface is created with pictures of the components in the same arrangement as the set up to enable a user to identify key parts. The user can also choose to override the SC function and turn on the cleaning process at a set time or adjust the criteria that triggers cleaning.

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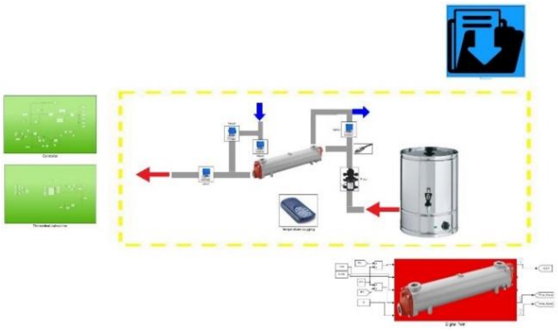

Fig. 4 - Simulink model: Controllers are shown in the green boxes, data storage in the blue, virtual model in red, and virtual representation in the yellow.

3.4. *Step 4 – Data exchange system*

Fig. 3 displays a diagram of the connection between the DT and the physical asses and how data is transferred and stored. Data transfer happens using serial USB connections between the Arduino Mega, Sensors and the computer.

3.5. Step 5 – Analysis

Data recorded from temperature and flow rate sensors is used in the HX Simscape model to predict the performance. The Simscape model in Simulink uses the Number of Transfer Units (NTU) method to calculate the expected outlet temperatures. The equations implemented in the block can be found in [15].

During operation of a clean HX there was a deviation of up to +/-2 ºC from simulated temperatures and those actually produced. This is due to the simulation using an estimated overall heat transfer coefficient (UA) which does not represent the actual UA for the HX. The UA value accuracy can be improved in the model by using stored data from the clean operations of the HX to predict the UA value based on the flow rate and temperatures into the HX. However, the accuracy of +/-2 ºC is sufficient for this application, especially as the accuracy of the temperatures recorded is limited to +/-1 ºC.

3.6. Step 6 – Develop actions (self-cleaning actions)

The key action that the DT triggers is the SC process. The key steps and rules the DT follows are:

1. Calculate difference between sensor output temperature and simulation output temperatures.
2. If the difference is greater than 5 °C then fouling check is triggered.
   - The fouling check tests every 100 seconds for 600 seconds (6 readings) if a deviation of 5 °C exists for the majority of the 6 readings then cleaning is triggered.
3. If the cleaning is triggered the controller switches to the *SE controller* mode otherwise it continues using the *Operation controller* mode and rests to step 1.
4. The SE controller switches off the pump and switches the valves to divert the mains water through the HX. Cleaning occurs for a set time of 300 seconds before returning to the Operation controller mode and step 1.

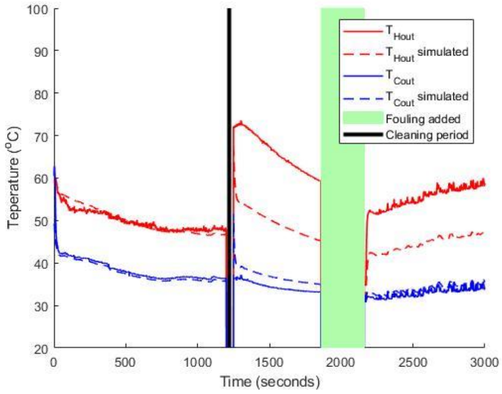

Fig. 5 – Real and simulated outlet temperatures recorded from the HX and DT simulation. The black line shows where fouling is added, and the green area shows where cleaning occurred.

A difference of 5 °C for only a few seconds is not sufficient to trigger the SC because this could be due to factors such as sensor error or a change not yet registered in the HX model. 600 seconds was used as the set time because this allows sufficient time for the heat transfer to reach steady state and multiple readings to be taken. Change in pressure readings can also indicate fouling but this has not been implemented in this research.

Designing and testing of controllers was done in Simulink initially. A fouling signal was added to the HX model, which added fouling gradually over time; this was used to test the DT response to fouling before implementing it.

From lab test with different cleaning times it was observed that the most fouling removal occurred over the first 300 seconds. Depending on the fouling, HX design and cleaning flow rate the time for cleaning time required would change. A future development of the DT could self-adapt the cleaning time depending on fouling recorded.

3.7. Step 7 and 8 – Verify and validate

The DT meets all the requirements set out in section 3.1. Section 4 shows results of three test

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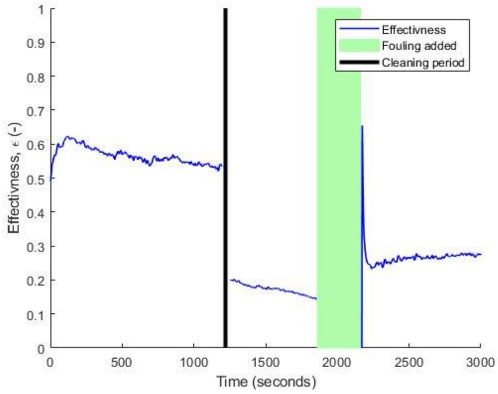

Fig. 6 – Effectiveness of HX calculated using outlet temperature readings. The black line shows where fouling is added and the green shaded area shows where cleaning occurred.

simulations run with fouling added to validate the DT and the SC mechanism.

4. Results

Three tests were carried out using the SC function and the DT. Wort was heated to 70-80 ºC and then cooled using the HX. After 1200 seconds of operation, the test was paused and fouling added to the inner HX tubes. Three experiments were conducted to test the performance of the SC response. Fig. 5 shows the outlet temperatures recorded by the sensors (solid lines) and those simulated by the DT (dotted line) in the first experiment. The black line shows the point fouling is added and the green shaded portion shows when cleaning took place. The temperatures rises and falls because the inlet temperature changes during each experiment. It is clear from the results that initially, the simulated and actual temperatures are close; however, after fouling is added, the temperatures of both the hot and cold fluids differ from the simulation, indicating fouling. This is picked up by the DT, and SC is triggered at 1850 seconds. After cleaning, there is a slight improvement, but there is still a difference in measured and simulated temperatures.

The flow rate of hot fluid is lower, causing a higher temperature drop and making it easier to notice the fouling. The ε of the HX in the first experiment is calculated and is shown in Fig. 6. Plotting ε makes it easier to see the difference in performance before and after cleaning.

The average effectiveness ($\bar{\varepsilon}$) for all three experiments is shown in Table 2; values for $\bar{\varepsilon}$ at the start (with a clean HX), after fouling is added and after cleaning are recorded. Due to the accuracy of thermocouples used, $\bar{\varepsilon}$ is only accurate to +/- 0.05. In all experiments, the fouling leads to a noticeable (>0.05) drop in $\bar{\varepsilon}$ and the cleaning returns some of $\bar{\varepsilon}$ lost initially, but not all. Cleaning in experiment 1 is the least effective, only improving $\bar{\varepsilon}$ by 0.06, while experiment 2 is the most effective with 0.22 improvement.

Table 2 – HX average effectiveness at the start before fouling, after fouling and after cleaning.

Experiment	Average effectiveness ($\bar{\varepsilon}$)			Percent $\bar{\varepsilon}$
	Start	Fouled	Cleaned	returned
1	0.57	0.18	0.24	15%
2	0.56	0.29	0.51	81%
3	0.59	0.30	0.45	52%

Table 3 – Estimated total heat transfer (Q) with and without cleaning in each experiment and extra time needed to run experiment without cleaning to get the same heat transfer.

Experiment	Q with (kJ)	Q without (kJ)	Extra time needed (s)
1	8064	8064	0
2	10440	9552	383
3	10344	9984	150

Table 3 shows the estimated total heat transfer during each 3000 second long experiment (Q_{clean}) with cleaning. An estimate is also shown for the total heat transfer if there was no cleaning (Q_{None}); this estimate assumes the $\bar{\varepsilon}$ stays at the fouled value in Table for the remaining experiment time. For two experiments, heat transfer is lower; therefore, a longer operating time would be needed to achieve the same heat transfer. The required extended time is also shown in Table 3. For experiment one, no extra operation time would be required. However, for experiment two and three, 383 and 150 seconds of extra operation would be needed, indicating that even for this short experiment the using the SC system is advantageous. In practice the HX would be in operation for much longer than 3000 seconds altering this extra time and the difference in total heat transferred.

5. Discussion and conclusion

This research presents the first example of a DT designed to autonomously manage a SE function in the form of a SC HX. The DT successfully utilised sensor inputs to identify and manage a SC function built into the HX. The DT also provided a basic user display of the data and interface which can allow a user to change when SC is triggered. Three successful tests were conducted, and the results are shown in section 4.

The cleaning does not have the same impact in each test and should ideally return the system to its original $\bar{\varepsilon}$. Differences in cleaning performance could firstly be due to differences in fouling quantity, for example in experiment 1 a large drop in

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effectiveness is seen possible due to heavier fouling which is harder to clean. Secondly, accuracy from the thermocouples causes a large error in $\bar{\varepsilon}$ (+/- 0.05) relative to the difference in $\bar{\varepsilon}$ fouled and $\bar{\varepsilon}$ clean (0.17, 0.19 and 0.29), making it hard to register fouling and removal accurately.

One cleaning cycle is clearly insufficient to clean the HX fully. The DT can still recognise that the cleaning has not been effective and could implement further cleaning cycles if needed in future tests.

The SC mechanism only uses a simple backflow of water to clean the HX. The cleaning could be made more effective by implementing other cleaning methods such as mechanical scrapers, cleaning balls or chemical cleaning agents. Scrapers would be the most reliable and remove a large amount of fouling but often leave a thin layer behind. Chemicals and balls would be less effective as they may not penetrate all fouled pipes evenly. The addition of a DT with cleaning methods would not directly improve the cleaning performance unless it was directly able to alter the cleaning settings. The DT could model cleaning processes or use previous data to optimise the cleaning settings and cleaning time to improve the performance.

The DT could be improved by giving it control of the pump flow rates. This would enable the DT to self-optimise heat transfer during normal operation by changing flow rates to achieve a set temperature, as done in previous research [12].

The simulations conducted are relatively simple and do not require significant computational power, enabling all processing to happen in real-time. More complex simulations would be harder to process in real-time on Simulink.

5.1. Future research

The first potential area of future research is implementing more complex cleaning methods; this current research could be expanded to use multiple cleaning methods, possibly drawing on the SE complexity framework [16] created by the authors. Future tests should also run the SC repeatedly until the original performance has been returned.

Secondly, the design of DT for SE could be explored further. SE systems are designed to be fully autonomous and not require user intervention; however, initially, operators may not trust the SE system and are likely to want to have the ability to take over control of the SE if required. Having a DT could provide the operator with feedback on the performance of the SE system and a user interface to interact with it if needed. The process and method used to design DT for SE should be explored further.

Acknowledgements

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