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Design and complexity evaluation of a self-cleaning heat exchanger

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A B S T R A C T

Self-engineering (SE) systems have valuable abilities to register and respond to lost function and return it. A self-cleaning (SC) system was designed for effective automated cleaning of a heat exchanger (HX) fouled by brewing wort. The system uses temperature outputs in a Digital Twin (DT) simulation and a controller to identify when fouling occurs and trigger a cleaning response. This paper utilises the SE complexity framework and investigates the effectiveness of different complexity designs. Three levels are created for each factor of the framework (repeatability, redundancy and self-control). For repeatability, the number of cleaning cycles was changed, while for redundancy, the flow rate was changed. For self-control, the cleaning mechanism was changed; pulses and foam balls were both used as the cleaning mechanisms. Balls were used to block pipes and redirect flow. An orthogonal matrix is used to reduce the number of experiments. SC effectiveness was measured for each cleaning cycle, and the results were evaluated. Cleaning with the max flow rate (0.21 kg s^{-1}) and using balls and pulses together provided the most effective cleaning, while the worst was with a low flow rate (0.09 kg s^{-1}) and just pulses. Further experiments verified these results and showed that better cleaning settings could lower water use in cleaning. A longer simulation demonstrated when the SC system would be stopped.

1. Introduction

Heat exchangers (HXs) transfer heat between two fluid streams. One of the most common types of heat exchangers used in process industries is the shell and tube heat exchanger (STHX). Its popular robust design allows a wide range of pressures and temperature flows to be used. Applications for STHX include heat recovery from thermodynamic cycles [1], wastewater heat recovery [2,3], oil cooling [4], food heating [5], crude oil processing [6,7], evaporation and condensation of steam [8], or industrial chemical plant cooling [9]. Many of these processes use water or aqueous solutions on one or both sides of the HX.

Fouling builds up from the deposition and accumulation of unwanted materials such as scale, algae, suspended solids and insoluble salts on the internal or external surfaces. This impedes the heat transfer in the exchanger and wastes processing time and energy. Many plate HX are designed to be easily disassembled to allow access to heat transfer surfaces for cleaning. Removing the heat transfer tube stack in an STHX can be complex; once removed, visual inspection and cleaning inside tubes are difficult without an endoscope camera.

Fouling is prevented and reduced by careful HX design, often using plates, spirals, corrugated surfaces, or fins to increase turbulence [10]. However, these methods do not completely stop fouling; further periodic cleaning is often needed during operation (on-line) or in pauses in operation (off-line). In many industries, such as food processing, clean-in-place (CIP) systems are used to clean and disinfect HXs and other equipment. CIP systems are generally automated and use a large amount of energy and water [11]. Other cleaning methods exist as outlined in Section 1.2; however, in all these systems, the final decision to clean is initiated by the plant operator or at a set time such as between operations; the decision is not taken autonomously based on the state of equipment. An intelligent system is needed to automatically recognise fouling has occurred and take action to remove the fouling without human intervention. This work investigates the design of a self-engineering (SE) system using a self-cleaning (SC) function in an HX. The system created could be used for rinsing in a CIP system or as a standalone cleaning system depending on fouling severity.

1.1. Self-engineering and complexity

A SE system is defined as: "An ability designed and built into a system to independently identify any loss or potential loss of function, and then automatically restore the functionality fully or partially to maintain its availability and improve system resilience" [12]. The four key characteristics are:

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Nomenclature

C_C	$= c_{p,C}\ \dot{m}_C$ [W°C $^{-1}$]
C_H	$= c_{p,H}\ \dot{m}_H$ [W°C $^{-1}$]
C_r	$= C_C/C_H$ [-]
$c_{p,C}$	Specific heat capacity [J°C $^{-1}$ kg^{-1}]
$c_{p,H}$	Specific heat capacity [J°C $^{-1}$ kg^{-1}]
ε	HX effectiveness [-]
ε_{Clean}	HX effectiveness before fouling [-]
ε_{DT}	HX effectiveness in DT simulation [-]
ε_{Foul}	HX effectiveness with fouling [-]
ε_{End}	HX effectiveness after cleaning [-]
$E_{SC}SC$	effectiveness [-]
$E_{SC_{Best}}$	Simulated degrading SC effectiveness best possible performance [-]
$E_{SC_{Daily}}$	Simulated degrading SC effectiveness for daily cleaning [-]
$\dot{m}_C$	Mass flow rate cold side (tap water) [kg s^{-1}]
$\dot{m}_H$	Mass flow rate hot side (wort) [kg s^{-1}]
M_W	Total water used for cleaning [kg]
NTU	Number of Transfer Units [-]
η	Signal-to-noise ratio [-]
η_{mean}	Mean signal-to-noise ratio [-]
$\dot{Q}$	Heat transfer in HX [W]
T_{Cin}	Cold inlet temperature (tap water) [°C]
T_{Cout}	Cold outlet temperature (tap water) [°C]
T_{Hin}	Hot inlet temperature (wort) [°C]
T_{Hout}	Hot outlet temperature (wort) [°C]
$T_{Cin,DT}$	DT simulated cold inlet temperature (tap water) [°C]
$T_{Cout.DT}$	DT simulated cold outlet temperature (tap water) [°C]
$T_{Hin.DT}$	DT simulated hot inlet temperature (wort) [°C]
$T_{Hout,DT}$	DT simulated hot outlet temperature (wort) [°C]
UA	Overall heat transfer coefficient [W°C $^{-1}$]

Acronyms

CIP	Clean-in-place
DT	Digital Twin
HX	Heat Exchanger
SC	Self-Cleaning
SE	Self-Engineering
STHX	Shell and Tube Heat Exchanger

1) It must have the ability to restore or partially restore lost function or capacity.
2) It must be built into the system.
3) The system should avoid or reduce maintenance, prolong life and/or increase the system resilience and robustness.
4) No human or operator intervention; any process, response and behaviour should be automatic.

Examples of previous SE systems include self-healing materials [13,14], self-adapting robotics [15], self-strengthening materials [16] or self-reconfiguring electronics [17] (also called built-in self-repair). Advancements in machine learning for monitoring and diagnostic application and more automation capabilities could lead to development of new SE systems.

The design and implementation of a SE system can increase the complexity of an existing system. Complex engineering systems can be difficult to change, upgrade, service or predict [18]. Previous authors have created frameworks to reduce design complexity [19]. However, identifying and managing rather than reducing design complexity can be useful because complexity can be needed for innovative or competitive products [20]. An existing framework for identifying complexity in SE systems highlighted three key factors that contribute to complexity [21]. Firstly, repeatability, the quantity of times a SE system can respond to a lost function. Secondly, the quantity of redundancy used in the system. Lastly, self-control, with centrally controlled systems being less complex than systems with multiple or interacting control mechanisms Fig. 1. is a visual diagram of the SE complexity framework and levels.

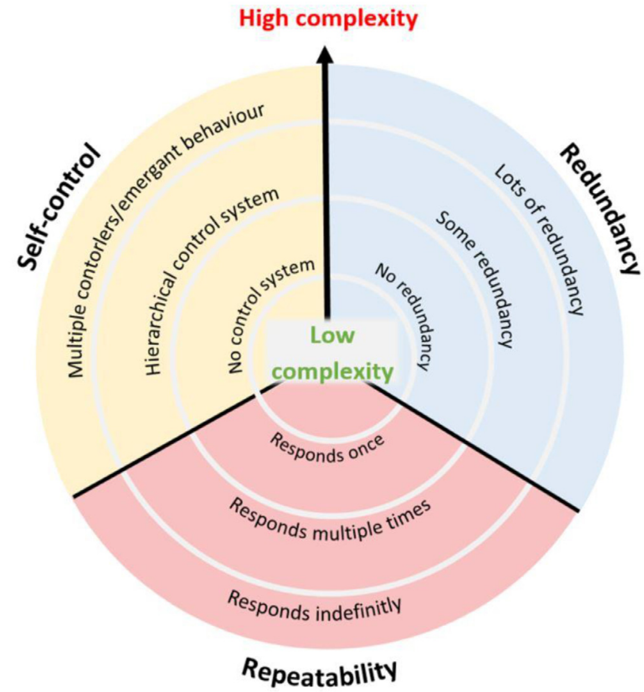

Fig. 1. Diagram showing the high and low complexity levels for the SE complexity framework, replicated with permission from [21].

Previous work on SE has primarily focused on theoretical evaluations [12,22]. This study investigates the design of an SC HX and the impact on the performance of changing levels of complexity (high, medium and low).

1.2. Previous fouling cleaning research

1.2.1. Self-cleaning coatings and materials

In engineering, SC is predominantly used to describe hydrophobic materials [23,24]; this type of SC is an example of robust design but not SE because the hydrophobic surface prevents the build-up of fouling by discouraging adhesion of material and water. Previous studies have applied hydrophobic coatings to plate HX [25,26], shell and tube HX [27] or brazed aluminium HX [28] to reduce fouling and thermal resistance from fouling. The long-term effect of damage or erosion on these coatings needs further investigation. Other SC surface modifications include using dimples on a surface to induce secondary flows [29]. Applying these coatings or surface changes can help prevent the build of fouling or make it easier to remove, but it does not remove the need for cleaning actions completely.

1.2.2. Self-cleaning filters

A SE SC response is a system that can automatically identify fouling and initiates a cleaning action to remove it when needed. This research focuses on these types of SC systems.

SC filters are often used in water processing applications. The most common method uses a backwash of fluid to dislodges fouling [30]. Other techniques include jets of water directed at or across the filter [31], ultrasound waves [32], or pulses of 40kV sparks to dislodge scaling fouling [33]. Cleaning tends to occur

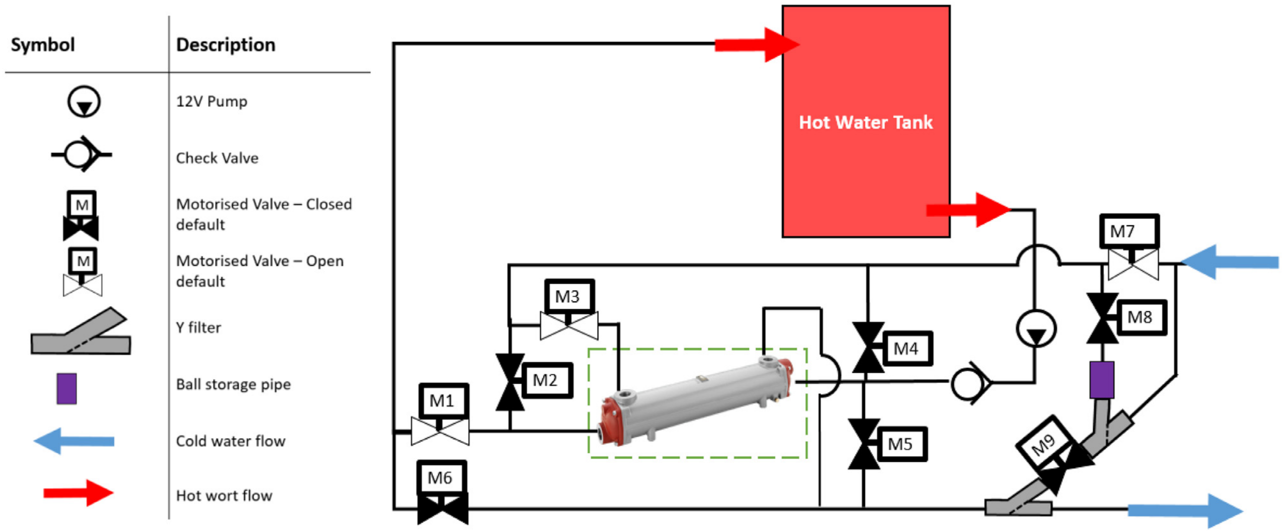

Fig. 2. Diagram of SC HX test rig used in all experiments. Positions of stainless steel pipes, filter, 12V DC pump and motorised valves are all shown. The key shows the corresponding symbols used. Hot wort flows on the hot side of the HX, while tap water is used for the cold shell side.

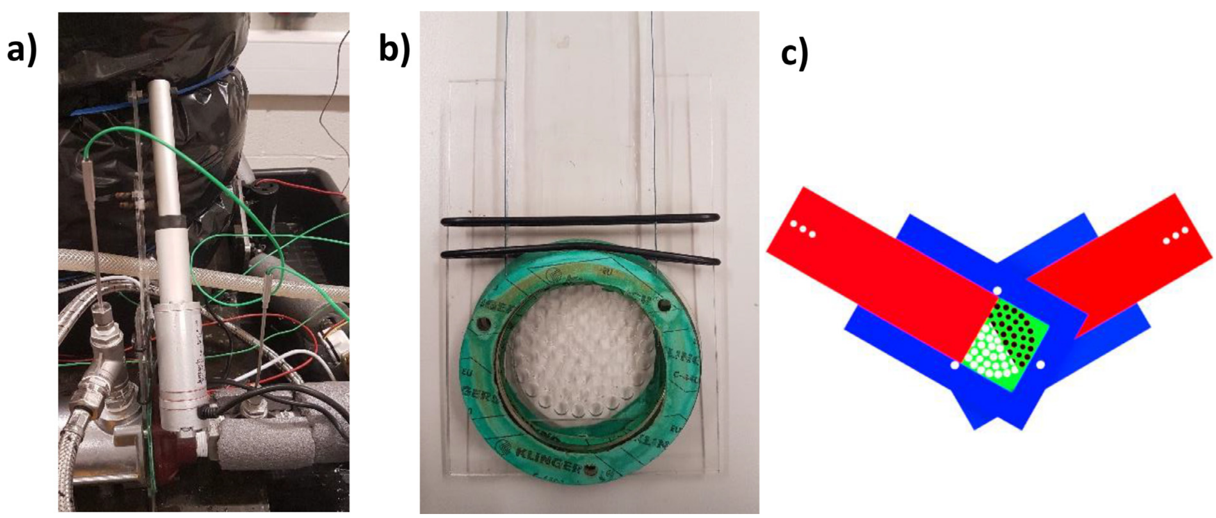

Fig. 3. Gate constructed to block HX pipes and force flow through other pipes, a) picture in operation, b) picture of parts used, and c) CAD model of two gate together.

at regular intervals during operation [34]. However, some filters record the pressure and automatically initiate cleaning of the filters creating a complete autonomous SE SC system [31].

1.2.3. Cleaning of heat exchangers

Mechanical cleaning methods for HX includes inserting brushes, balls, coils or wire inserts; these can often be done on-line by adding them to the working fluid or off-line by adding them to the cleaning fluid. Other off-line cleaning techniques which requires no disassembly include ice pigging [35,36] or pulsing cleaning water. More intensive jet washing, sandblasting, drilling or manual brushing requires disassembly and can take days. In this paper, water was used to clean the HX with cleaning balls and a pulsing flow rate.

Gillham et al. [37] utilised pulsating flow to increase cleaning rates inside HX pipes fouled by whey. Augustin et al. [38] noted similar results and found pulsing created high periodic acceleration at the wall, speeding up fouling removal in cleaned food processing pipes. Flow pulsations with the on-off flow [39] and bellows and pistons [37] have been proven successful. In this research, the flow is stopped and started because this could be achieved without adding a bellow or piston.

Cleaning balls are often added to hard water to remove any calcium carbonate building up as scaling on HX pipe surfaces. Balls are small ceramic balls to erode fouling as in fluidised bed HX [40], or slightly larger than the pipe diameter and made of rubber or foam to brush fouling off [41]. In most research experiments, a single pipe HX is used, meaning all balls are forced through one hole, but limiting possible HX used [42]. When multiple pipes are cleaned, such as in STHX, there is no mechanism to guarantee balls clean all the pipes [8,43]. Instead, authors tend to optimistically state that high quantities of balls guarantees that all pipes are reached. This problem has been addressed later in the study with an alternative method of using cleaning balls presented.

1.3. Paper structure

The study aims to create an effective SE SC mechanism for an STHX. Secondly, it aims to investigate the impact on the performance of utilising different levels of complexity for repeatability, redundancy and self-control. Section 2 provides details on the experimental methodology and test rig used in experiments. Section 3 outlines the results of experiments and identifies which factor has the largest impact on SC performance, Section 3 also dis-

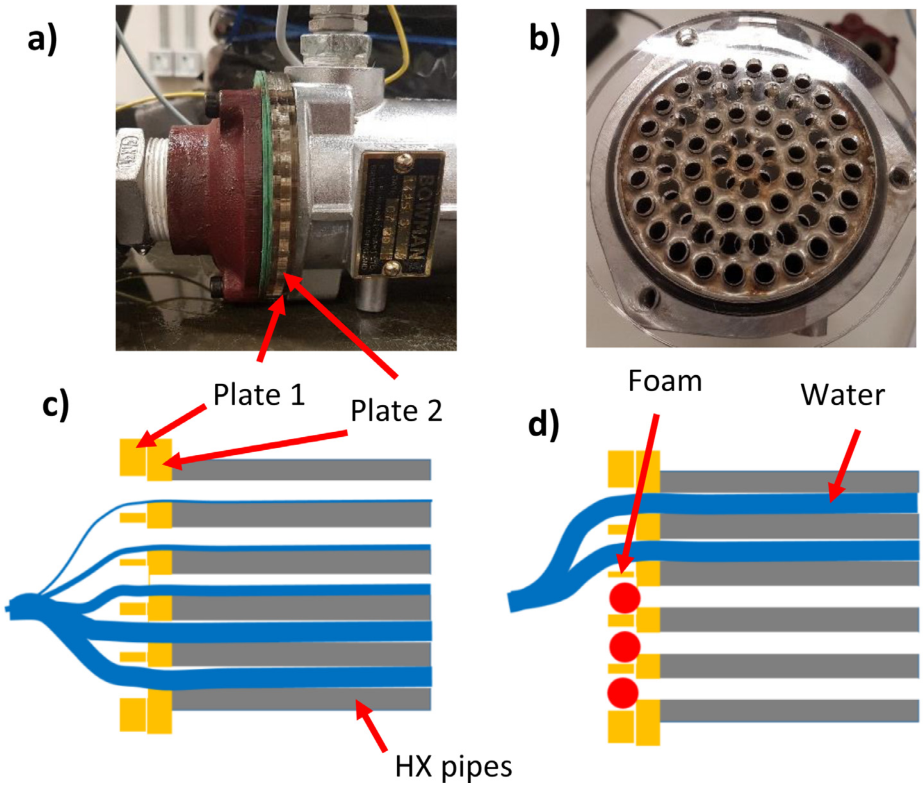

Fig. 4. a) Picture of HX with plates added to catch balls in operation; b) picture of plates sitting on the end of the HX (holes not lined up); c) diagram showing flow of water in HX without balls added; d) diagram showing flow of water in HX with balls added.

cusses the findings. Finally, Section 4 presents the conclusions of the paper.

2. Experiential methods

Previous cleaning experiments for breweries inspired the experiments conducted in this study. Goode et al. [44] presented a summary of the processes in a brewery and the different fouling encountered at each phase of production. This research focuses on wort fouling in a HX used in wort cooling.

Wort is a mixture of malted barley, hops, yeast and water; after being boiled to remove microbes, it has to be cooled quickly to room temperature to allow fermentation to begin [45]. Fouling impedes the performance of the HX, leading to longer processing times or harbouring bacteria that can contaminate future operations. Fouling builds up over time in the HX and can take months to form. To enable multiple experiments and cleaning cycles to be tested, fouling was added in the form of malt extract syrup (Cedarex Light syrup from Muntons ingredients). Similar malt extracts have been used as fouling in experiments previously [46–48]. The same syrup is combined with water to make the main hot wort cooled in the HX. It should be noted that fouling deposits created are only an approximation of the fouling experienced in the brewing industry and are primarily used to allow repeated experiments in a shorter space of time.

2.1. Experimental set up

The SC HX is designed to meet all the characteristics of, and respond as, a complete SE system. A Bowman EC120 STHX with a single pass counter-current arrangement was used in this research.

Nine motorised valves, one check valve and a 12V DC diaphragm pump were used along with the HX. In a standard operating mode, hot wort at inlet temperatures of 70 to 80°C was pumped through the inner tubes of the HX at 0.035 kg s^{-1} and cooled before being returned to the main tank. Cold tap water at 18-20°C and mains pressure (1 bar) is pumped through the outer heat shell side HX at 0.15 kg s^{-1}. A diagram of the test rig is shown in Fig. 2. Further details on the cleaning mechanisms are given in the next section (2.2.). Motorised valves were controlled by an Arduino Mega, which received and transmitted signals to a Simulink programme running a DT (see Section 2.4. for details). Motorised valves in white on Fig 2 (M1, M3 and M7) show ones left open for cooling the wort. Black valves are closed until needed for cleaning. Y-filters are used to catch balls so they can be reused.

PT100 probes for measuring temperature were placed to measure the inlet and outlet of the hot and cold flows (T_{Hout}, T_{Hin}, T_{Cout} and T_{Cin}). A differential pressure sensor (MP3V5010DP by NXP) measured pressure loss through the HX tubes. Hall Effect flow rate sensors measured the flow rate through both sides of the HX. Flow rate and pressure voltage readings were recorded and transmitted using the Arduino Mega.

2.2. Cleaning mechanisms

The research aimed to test different complexity levels; therefore, different cleaning mechanisms were designed to represent different self-control complexity levels. The three cleaning mechanisms are detailed in this section; all use a backflow of tap water for 300 seconds, but different methods are used in each to boost cleaning. Only two of the mechanisms were utilised in the final experiments.

2.2.1. Pulse cleaning mechanism

Initially, valves M1, M3 and M7 (see Fig 2) are closed and then valves M2, M5 and M7 are opened to allow a backflow of water. Valve M2 is oscillated open for 40 seconds and closed for 5 seconds to create pulsating bursts of flow. This is a central self-control method because the main controller manages the valves. The pulse occurs across the whole set of HX tubes and cannot target specific tubes.

2.2.2. Gates for blocking flow

If there is uneven fouling or fouling in a section of pipes, pulses cannot be targeted at just that tube to aid cleaning. A method was proposed using gates to block flow to certain HX pipes to increase water flow and cleaning in other pipes which may be more prone to fouling, such as pipes on the outer edges. The design created is shown in operation in Fig 3 a). A linear actuator was used to move a gate (a rectangular piece) made of acrylic up and own inside a U-shaped frame (see Fig 3 b)). Plates with holes matching the holes on the shell and tube HX were used on either side of the gate to create a better seal over the pipes. It was held in place by bolts holding the HX end caps in place. During cleaning, the linear actuator would move the gate up and down, blocking off the flow. As more pipes are blocked, the flow rate in the remaining increased further and creates more effective cleaning. The aim was to use a combination of two gates to allow more control of the blocked section (see Fig 3 c)).

The problem with this mechanism is that no effective seal could be maintained between the moving gate part and the U-shaped frame. Small leakages occurred, which grew bigger when the gate was closed. No effective and resilient method of sealing the moving gate was found, leading to this method being abandoned.

2.2.3. Ball cleaning method

The last cleaning method used foam balls. Initially, 5mm balls were going to be pushed through the HX to clean fouling; however, in initial tests, cleaning was not evenly distributed, and balls could be left in pipes. Pipes with high levels of fouling will have a higher pressure drop and slower flow rate. It was theorised that balls are pulled towards higher flow rate tubes, leading to cleaning of pipes that are already cleanest. A new approach was proposed to deal with this problem. Larger 6mm foam balls and a set of 5mm thick acrylic plates with holes were used, see Fig. 4. Plate 2 has smaller 4mm holes that stop the balls from going into the HX (see Fig. 4); balls are then held in this place in larger (6.25mm) holes in plate 1, see Fig. 4 d). The effect is that more of the flow is directed to other pipes which previously had less cleaning flow (shown in Fig. 4 c) and d)). This is a localised cleaning method where the balls' release is centrally controlled, but the flow and fouling in each tube impacts the ball position and which tubes are blocked; this creates a complex local response that is hard to predict. The authors are not aware of this method being used previously for cleaning.

For the first 150 seconds, only M2, M5 and M7 are open to allow water to clean pipes. At 140 seconds, M8 is opened, and M7 is closed, forcing 30 balls out towards the 61 HX pipes. At 280 seconds, flow is reversed for 20 seconds with M4, M6 and M9 opened to allow the balls to be pushed out of the plates and caught.

2.3. Different complexity levels

The SE complexity framework outlined in Section 1.1 [21] defines high, medium and low complexity for redundancy, repeatability and self-control. Here specific levels for the SC system are outlined; the different levels can be seen in Table 1. For redundancy, high, medium and low complexity was replicated by utilising three different flow rates of cleaning water achieved by throttling the inlet valve to fully open, ½ closed and ¾ closed. The complexity levels of self-control were implemented with different cleaning methods as outlined in Section 2.2. The lowest self-control was controlled by using different cleaning methods and combinations, as discussed in Section 2.2.

Table 1
Table of the three complexity factors used and the three different high medium and low complexity level for each factor.

Level	Repeatability	Redundancy	Self-control
Low	1 cleaning cycle	0.09 kg s^{-1}	Pulses cleaning
Medium	3 cleaning cycle	0.15 kg s^{-1}	Balls cleaning
High	7 cleaning cycle	0.21 kg s^{-1}	Pulses and balls cleaning

Table 2
Taguchi orthogonal array (L9) with the experiment settings used for each run. Each setting represents high, medium or low for a complexity factor.

Run #	Repeatability	Redundancy	Self-control
1	1 cycle	0.09 kg s^{-1}	Pulse
2	1 cycle	0.15 kg s^{-1}	Ball
3	1 cycle	0.21 kg s^{-1}	Pulse and balls
4	3 cycles	0.09 kg s^{-1}	Ball
5	3 cycles	0.15 kg s^{-1}	Pulse and balls
6	3 cycles	0.21 kg s^{-1}	Pulse
7	7 cycles	0.09 kg s^{-1}	Pulse and balls
8	7 cycles	0.15 kg s^{-1}	Pulse
9	7 cycles	0.21 kg s^{-1}	Ball

Repeatability is the number of times a SE system can respond. This is harder to replicate in experiments because the SC system is designed to operate for many cycles with any settings used. Repeatability was investigated by conducting multiple fouling-cleaning cycles, which were removed, and new fouling added. The number of cycles tested was one, three and seven. Seven was the maximum number of cycles because this was the maximum that could be tested in a day of experimentation.

Taguchi experimental design method was used with an L9 orthogonal array to reduce experimental runs [49] Table 2. shows the nine experimental runs with the experimental setting used.

2.4. Digital Twin and control

A digital twin (DT) was created using Simulink for use in experiments. The DT consists of an ideal model of HX performance, a user display and data storage. Live and previous flow rate and temperature sensor data from the experiment as well as data produced by the HX model are held in the data storage. The user display outputs the sensor (T_{Hout}, T_{Cout}) and predicted ($T_{Hout,DT}$, $T_{Cout,DT}$) clean HX outlet temperatures to the operator Fig. 5. shows a diagram of the different physical components and how they link to the virtual system. All virtual space systems are run in a Simulink model.

The HX model in the DT simulates the HX performance assuming no fouling is present. The model is constantly updated with live sensor data of hot and cold input flow rate (m_H, m_C) and temperatures (T_{Hin}, T_{Cin}). Within Simulink, there are Simscape blocks for modelling thermal flows. The existing Simscape blocks were unsuitable for modelling the HX design, so a custom block was created using the Number of Transfer Units (NTU) method to calculate HX outputs. The equations used are detailed below in Eqs. (1)–(5), where $C_H = m_H\, c_{p,H}$ and $C_c = m_c\, c_{p,c}$.

$$C_r = \frac{C_H}{C_C} \tag{1}$$

$$NTU = \frac{UA}{\min(C_C, C_H)} = \frac{UA}{\mathrm{C_H}} \tag{2}$$

$$\varepsilon_{DT} = \frac{\dot{Q}}{\dot{Q}_{\max}} = \frac{\dot{Q}}{C_H(T_{Hin} - T_{Cin})} \tag{3}$$

$$\varepsilon_{DT} = \frac{1-\exp(-NTU(1-C_r))}{1-C_r\exp(-NTU(1-C_r))} \tag{4}$$

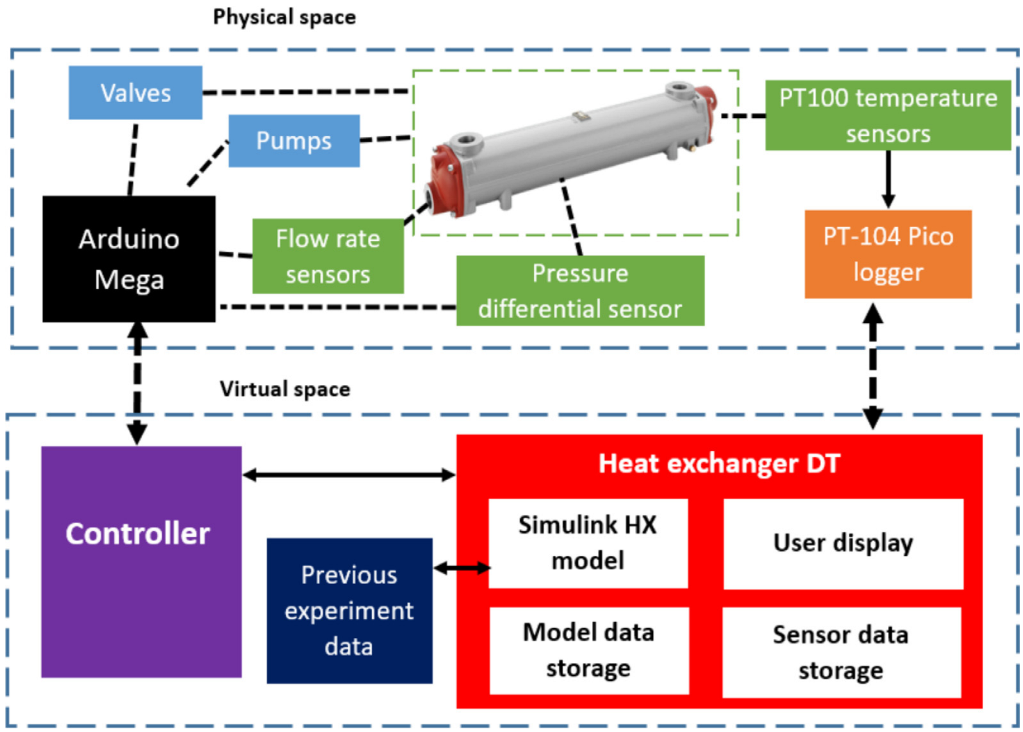

Fig. 5. Diagram showing the connection between the physical components, the DT (in red box) and the controller. There are four components in white that make up the DT. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

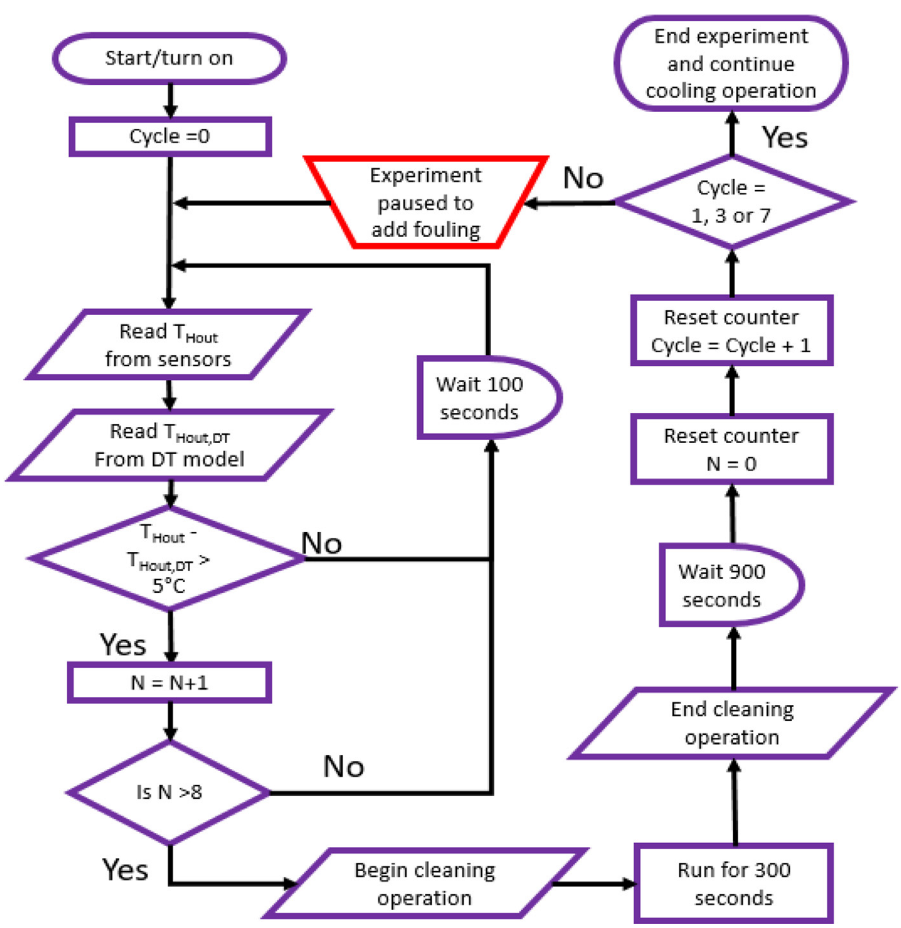

Fig. 6. Flow chart showing SC controller used in the experiments and the times when readings are taken. The red box shows when experiments are paused to remove and add new fouling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

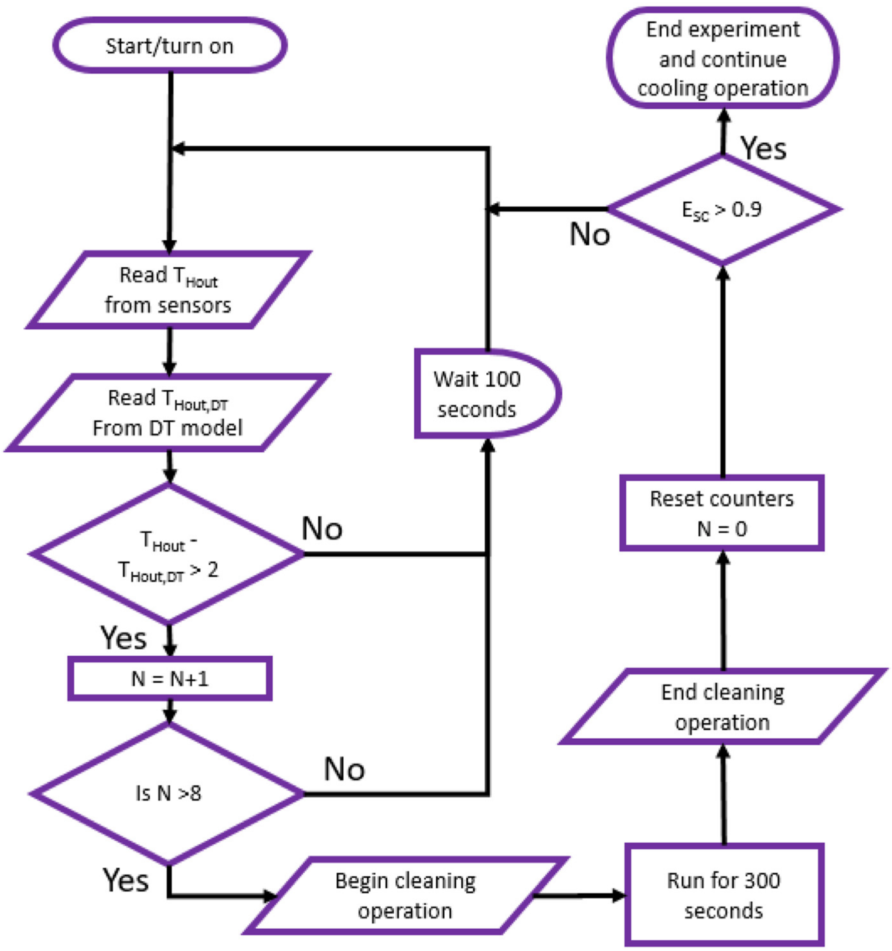

Fig. 7. Flow chart showing SC controller used in the validation experiments (section 3.4). Cleaning continues until a threshold of E_{SC} >0.9 is met.

$$\dot{Q} = C_H(T_{Hin} - T_{Hout,DT}) = C_C(T_{Cout,DT} - T_{Cin}) \quad (5)$$

The effectiveness of the HX in the DT model (ε_{DT}) is found using the NTU values. The unknown in the equation is the UA (total heat transfer coefficient and area). This can be calculated by summing convective and conduction heat transfer through the tubes to find a total thermal resistance. This was done initially, but it was found to be more accurate to use UA values collected from previous clean HX operations. A linear relationship for UA based on inlet temperature from temperature sensors was generated when the DT was started ($UA = f(T_{Hin}, T_{Cin})$); UA only varies slightly due to temperature and would change faster with flow rate change, but flow rate is kept constant in the experiments.

Fig. 6 shows a flow chart of the controller process. The model output ($T_{Hout,DT}$) is compared to the actual temperature sensor reading (T_{Hout}) to identify a difference between temperatures. It was observed that when the HX was clean, model and sensor readings could vary by up to +/-2°C from each other due to sensor response delay or natural fluctuation in T_{Hout}. A threshold value of $T_{Hout} - T_{Hout,DT} > 5°C$ was set; this allows fouling to be registered before it grows too high but prevents the 2°C variations being resisted mistakenly as fouling. The controller checks every 100 seconds, and each time $T_{Hout} - T_{Hout,DT} > 5°C$ is met a counter (N) increases by one. Nine instances of fouling are needed to trigger cleaning. This is because one increase in outlet temperature could be due to temporary fouling or a sensor error; using multiple measurements creates a checking system that tries to verify the presence of fouling. Utilising pressure or flow rate sensors could also verify the fouling is present, however, the sensors used did not accurately register fouling.

The controller in Fig. 6 shows the one used in experiments. A pause of 900 seconds follows cleaning to allow post-cleaning measurements. Then the number of cycles is recorded and checked against the number set for that experimental run. After these steps, the experiment is paused to add more fouling to the HX. In an industry operation, these three steps would not be required. Instead, a threshold value of SC effectiveness (E_{SC}) could be set; this is demonstrated in the controller diagram in Fig. 7 and E_{SC} is defined in Section 2.6.2.

2.5. Adding Fouling

Previous experiments have spread malt extract on surfaces and left it to dry in the air for 10 minutes [46,47]. Alternatively, fouling is adhered onto tubes with heat [48], though no details were given of the process used. Spreading the malt extract on to tubes was not possible in this experiment because the tubes were fixed in the HX. The malt extract application process used is shown in Fig. 8. A set amount of extract (0.4 kg) is poured on top of the tubes; this quantity was chosen because it consistently provided at least a 50% reduction in ε. Guide rails are used to hold the extract in a pool above the holes (Fig 8 a)). The end of the HX tubes are left open to allow air to escape and the malt extract to flow into the HX. Once the syrup has flowed into the tubes, it is turned horizontally and, a hairdryer is held at a 2cm distance from the tube end for 15 minutes at each end. The heat and air pushed the fouling along

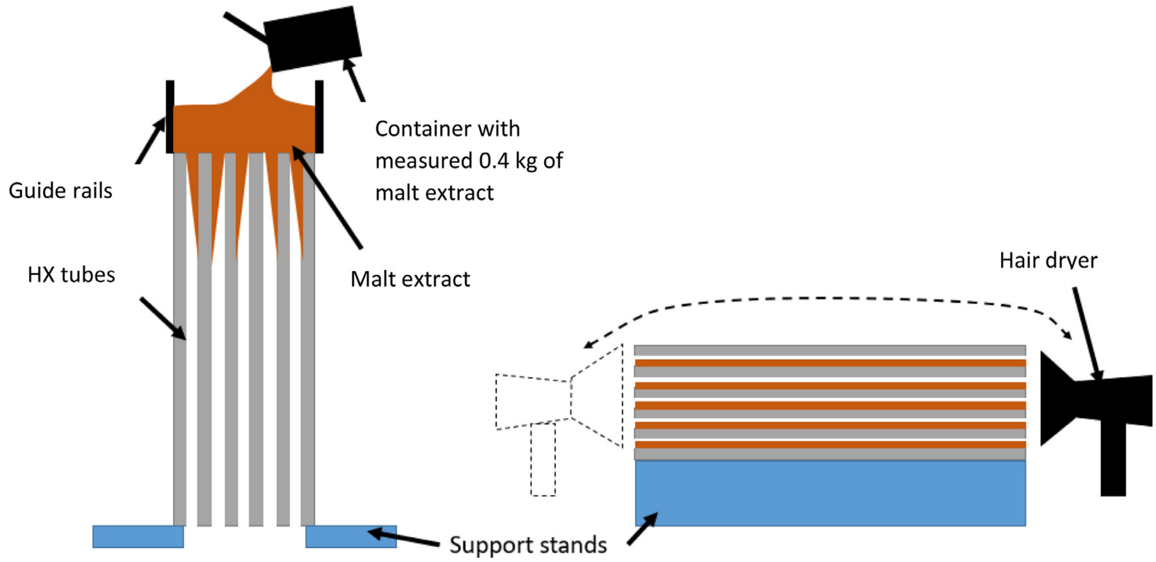

Fig. 8. Diagrams showing process of adding fouling to the HX, a) shows the fouling being poured in and b) uses a hair dryer to blow air into the HX.

the tube, helping it spread evenly and dry to the tube sides. The HX is then left for 10 minutes for the wort to cool down before the HX is reassembled. The fouling deposit created is predominantly a viscous liquid (Type 1) fouling as defined in [50,51].

2.6. Measurements

2.6.1. Temperature measurements

The temperatures were measured using PT100 probes on the outlets and inlets of the HX with an accuracy of 0.1°C. PT100 probes were held in place in the flow by compression fittings with threaded connectors. PT100 probes are attached to a TC-104 Pico data logger, which relays data via USB to a computer running the Simulink controller and DT.

2.6.2. SC effectiveness measurements

The most reliable way to predict fouling was by measuring temperature and calculating the effectiveness of the HX (ε), defined in Eqs. (1) and (2) [52].

$$\varepsilon = \frac{Actual\ heat\ transfer}{Maximum\ possible\ heat\ transfer} \tag{6}$$

$$\varepsilon = \frac{m_H c_{p,H} (T_{Hin} - T_{Hout})}{\min\left(m_C\, c_{p,C}, m_H\, c_{p,H}\right)(T_{Hin} - T_{Cin})} \tag{7}$$

The flow rate in the hot flow side is lower than the cold side meaning $m_H\, c_{p,H}$ cancels out leaving only temperatures to calculate ε. Values of ε indicates the amount of heat transferred; with fouling the ε value falls. By comparing values of ε from the clean starting HX (ε_{Clean}), the fouled HX (ε_{Foul}) and at the end after SC (ε_{End}), a total SC effectiveness (E_{SC}) can be found; see Eq. (3).

$$E_{SC} = \frac{\varepsilon_{End} - \varepsilon_{Foul}}{\varepsilon_{Clean} - \varepsilon_{Foul}} \tag{8}$$

The uncertainty of +/- 0.1°C in temperature readings propagates through to an average uncertainty of +/- 0.8% in ε and +/- 3.9% in final E_{SC} values.

2.6.3. Fouling measurements

Before new fouling was added for each new cycle, all 61 pipes were cleaned using a wire pipe cleaning brush Fig 9. a) shows the brush when fouling is found in tubes, and Fig. 9 b) is when it is clean. The total number of pipes still fouled at the end of an experiment was recorded to compare to the E_{SC} values. The biggest source of error in these measurements is human error, an error of +/- 1 pipe was considered appropriate for the recorded number of fouled pipes.

Table 3
Table of the uncertainties in experiment measurements taken.

Measurement	Error	Justification
Temperature	+/- 0.1 °C	Sensor resolution
Number of pipes fouled	+/- 1 pipe	Human error
Flow rate	+/- 0.001 kg s^{-1}	Sensor resolution
E_{SC}	0.016	Error propagation
ε	0.008	Error propagation
η	-0.30	Error propagation

2.6.4. Measurement uncertainty

All error measurements and sources of error are summarised in Table 3.

3. Results and discussion

3.1. Experimental results

One experiment was conducted for each of the settings outlined in Table 2, with the control system seen in Fig. 6 in Section 2.4. Initially, the HX is run clean with no fouling for 900 seconds to get an initial ε_{Clean} measurement, before fouling was added. The controller uses the DT model and sensor data to register fouling and initiates the SC response with the set complexity levels. After cleaning, the experiment ran for 900 seconds to get further measurements about the performance of the HX post-cleaning. If multiple cycles were used, the experiment was paused at set points, and new fouling was added. In total, the experiment runs 1-3 took 3000 s to complete, while runs 4-6 took 7200 s and runs 7-9 took 15600 s.

A graph of data from one experiment with seven cleaning cycles (run #7 in Table 2) is presented in Fig. 10. The points at which experiments were paused to add fouling are indicated using black lines, while periods of cleaning are shown in green. The bottom half of Fig 10 shows the temperature outputs from the HX alongside those predicted by the DT. Variation in outlet temperature oc-

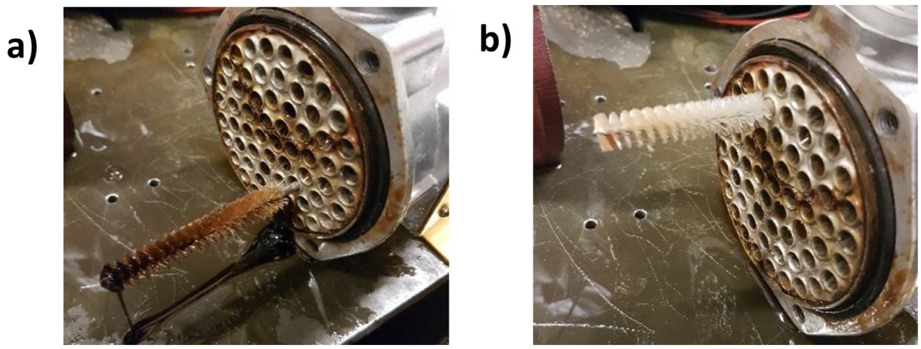

Fig. 9. Pictures of cleaning brush after cleaning HX pipes; a) shows brush after cleaning fouled pipes and b) shows clean brush when no fouling. The process was used to check number of pipes fouled and cleaned in experiments.

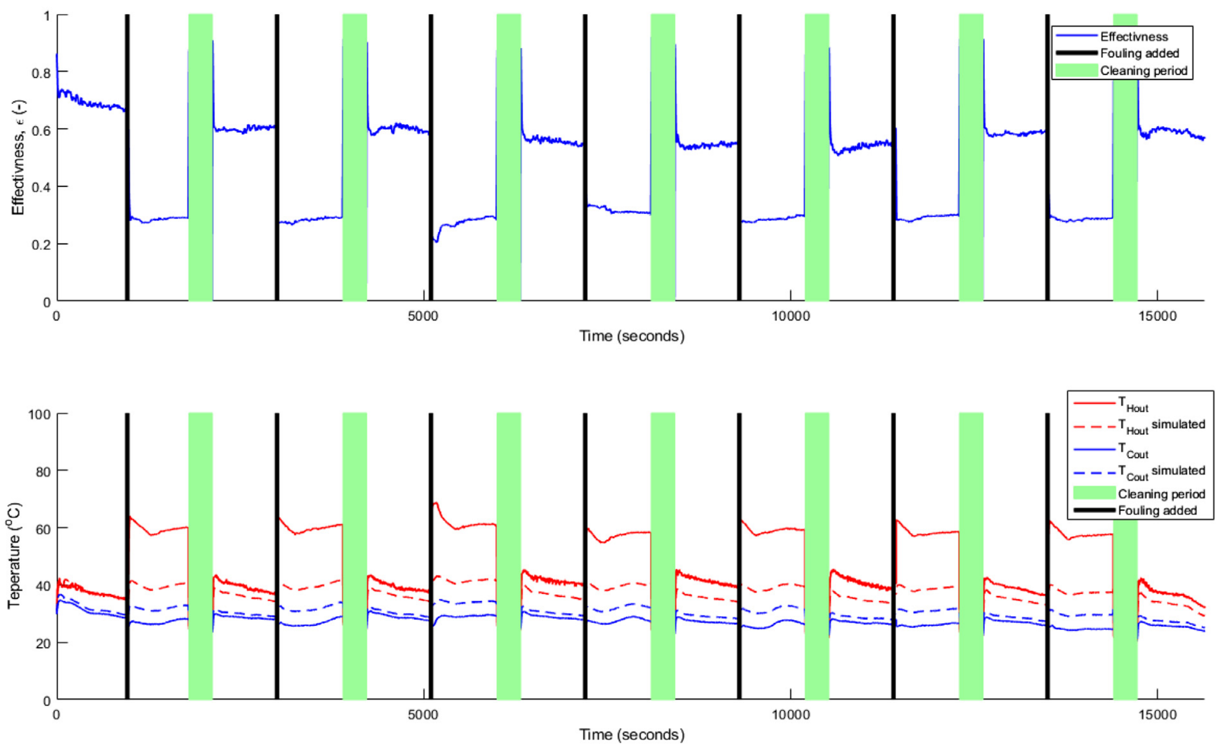

Fig. 10. Top: graph of the HX effectiveness, ε, over time. Bottom: graph of recorded temperature over time at HX hot outlet (red solid line) and cold outlet (blue solid line); dotted lines show the predicted temperatures from the DT. Black lines indicate where fouling is added, and green blocks show where cleaning occurred. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

curs because inlet tank temperature changed from 80 to 70°C during the experiment. The predicted temperatures in Fig. 10 are for a clean (no fouling) HX; initially they start close to the actual temperatures of the HX, but the addition of fouling causes them to deviate. Subsequent cleaning cycles also fail to remove the fouling fully leaving a difference in predicted and simulated temperatures.

The fouling impact is best viewed by observing ε (top graph of Fig. 10); fouling causes ε to fall from approximately 0.7 to 0.3; the cleaning is effective and returns ε to 0.6 – 0.65 ($E_{SC} = 0.72$). The total E_{SC} for each cycle is calculated and shown with the average value for the experiment run in Table 4.

Values of E_{SC} for all runs and cycles are shown in Table 4; they ranged from 0.89 at best for run #9 down to 0.20 for runs #1 and #8. The best SC runs are #3, #9 and #5; the only common factor is that balls are used in the cleaning. The two runs with the lowest mean E_{SC} both use pulses to clean the HX, indicating that pulses were a weaker cleaning method than balls.

There is also variation in cycle E_{SC} within experimental runs. The distribution of fouling in each tube could not be measured in experiments, meaning some variation may have occurred, leading to variation in E_{SC}. As noted in previous studies, creating replicable fouling deposits on small patches is difficult [47,53]; this becomes even harder with the larger surface area of a whole HX.

Table 4 also shows the signal-to-to noise ratio (η) for each run. Details on calculation of this value can be seen in section 3.3.

3.2. Pipe fouling measurements

For each E_{SC} value taken the number of pipes with fouling remaining is counted to help verify the E_{SC} measurements. An obvious negative correlation is shown in Fig. 11 between E_{SC} and number of pipes still fouled, indicating that E_{SC} is representative of the effectiveness of SC. The largest deviations are seen when 10-25 pipes are blocked; this probably occurs due to partially cleaned

Table 4
Results of E_{SC} recorded for each cleaning cycle and the mean of all cycles. The η ratio for each experimental run is shown at the end. Settings for each run are shown in Table 2.

Run #	Cycle 1	Cycle 2	SC effectiveness (E_{SC}) Cycle 3	Cycle 4	Cycle 5	Cycle 6	Cycle 7	Mean E_{SC}	η
1	0.20							0.20	-13.68
2	0.44							0.45	-7.04
3	0.85							0.85	-1.42
4	0.72	0.61	0.38					0.57	-5.82
5	0.81	0.92	0.91					0.88	-1.16
6	0.76	0.78	0.57					0.71	-3.28
7	0.72	0.73	0.64	0.56	0.58	0.69	0.71	0.66	-3.72
8	0.20	0.39	0.41	0.48	0.48	0.13	0.13	0.32	-13.72
9	0.98	0.86	0.93	0.88	0.66	0.99	0.91	0.89	-1.28

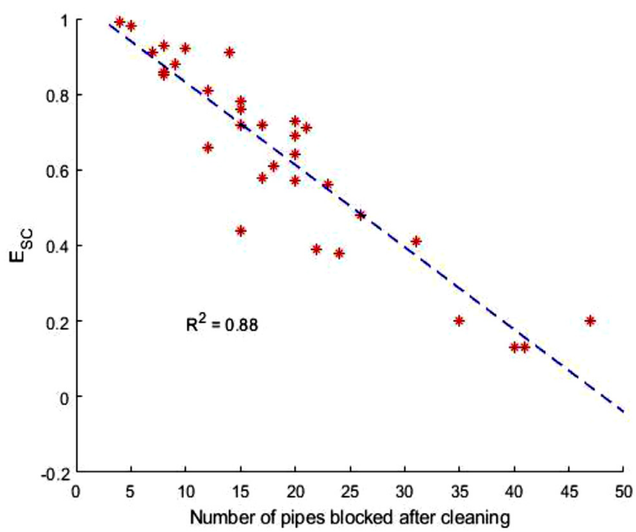

Fig. 11. Graph of number of pipes still fouled against E_{SC} values calculated with temperature readings.

pipes where some fouling has been removed but not all. With high and low E_{SC}, more pipes remain fully blocked or are totally clean, leading to more accurate readings.

3.3. Complexity levels

To identify the optimum settings from the nine experiments conducted, the signal-to-noise ratio (η) is found. A larger is better signal-to-noise ratio was used because the aim is to maximise E_{SC}. Eq. (9) (from Phandke, (1989)) is used to find η, where E_{SC} is the value recorded and n is the number of E_{SC} values recorded.

$$\eta = -10\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{E_{SC\,i}^{2}}\right) \tag{9}$$

The final results for each experimental run are calculated. Values for η are averaged together to find η_{mean} for each complexity factor (repeatability redundancy and self-control) and level (high, medium or low). The final results are plotted in Fig 12; results with higher η_{mean} are the optimum complexity levels for each factor that maximises cleaning performance. The range (highest minus lowest) score for each complexity factor indicates which factor has the greatest impact on E_{SC}. The final range and rank are shown in Table 5. Self-control complexity has the biggest impact on the cleaning, followed by redundancy then repeatability. The optimum performance for each is with high self-control, high redundancy and medium repeatability complexity levels. In physical settings, this is cleaning with pulse and balls, 0.21 kg s^{-1} flow rate

Table 5
η_{mean} for different levels of each complexity factor as displayed in Fig. 12. Range (highest minus lowest) and rank are shown. Self-control is rank 1 with the highest range and the factor with the biggest impact on E_{SC}. Repeatability has the smallest impact and is rank 3.

	Repeatability	Redundancy	Self-control
Low	-7.38	-7.74	-10.23
Medium	-3.42	-7.31	-4.71
High	-6.24	-1.99	-2.10
Range	3.96	5.75	8.13
Rank	3	2	1

and three cleaning cycles. The worst complexity is low in all three factors with pulses, 0.09 kg s^{-1} rate and only one cleaning cycle.

The best E_{SC} tends to be at the highest complexity levels, indicating the final optimised design will have a higher level of complexity. This could make the system harder to maintain or change if needed. For future SE system design, a similar design process could be useful by helping ensure designers are aware of the complexity and effectiveness of different designs before implementing them.

3.3.1. Self-control (cleaning method)

From the three complexity factors, self-control has the biggest impact on E_{SC}. As noted in Section 3.1, the best performing runs all use balls; this is further backed by Fig. 12 a), which shows using balls and pulses together produces the best performance. Utilising balls to block pipes and increase flow in other pipes appears to work to improve E_{SC} noticeably. This differs from previous work where balls are forced through to erode fouling in a single tube HX [42]. However, further studies would be needed to observe if the balls are blocking the cleaner tubes or randomly positioned. The use of balls here would also be unsuitable for plate HXs, which have wide, narrow channels; another mechanism is needed to block individual plate channels and perform selective cleaning.

Using pulses on their own did not prove effective, but it did increase cleaning when combined with ball cleaning, as shown in Fig 12 a). As noted in previous research, pulses are most effective at removing fouling when the pulsation amplitude is high enough to cause the flow to reverse its current direction temporarily [38,54]. The pulsation in this research could not achieve this because it would interfere with the balls and remove them from the pipes they are blocking.

3.3.2. Redundancy

Redundancy has the second largest impact on E_{SC}. This study, and previous research [53], show that increasing flow rate (redundancy) improves cleaning fouling. However, Fig 12 b) shows the impact is smaller for low to medium complexity increase than medium to high. Flow rates above the max 0.21 kg s^{-1} could have

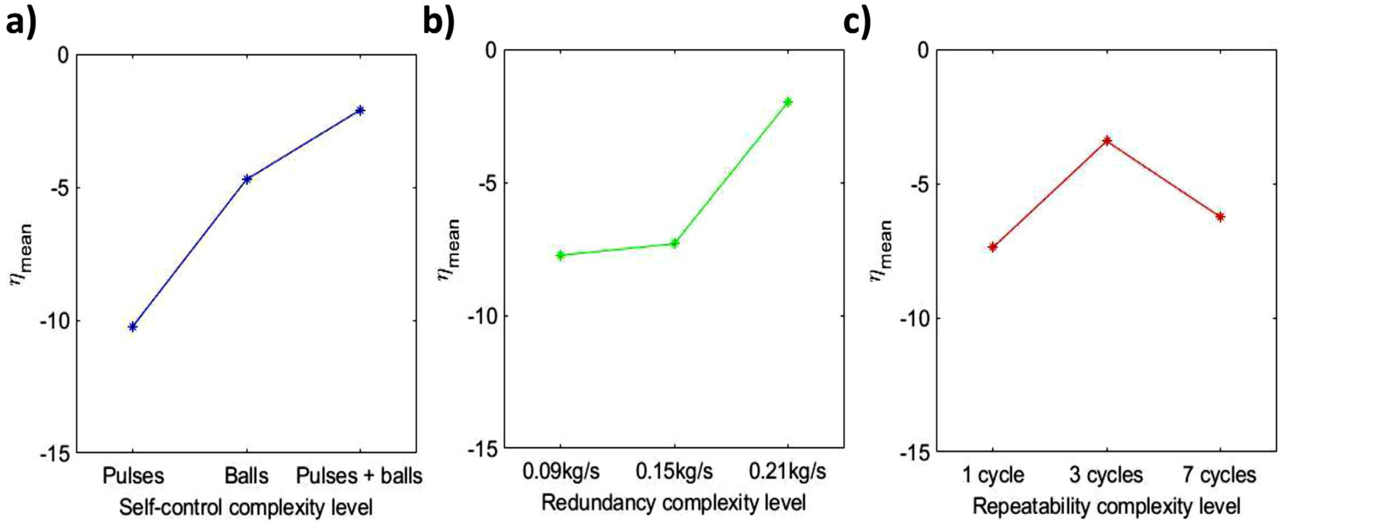

Fig. 12. Graphs showing the mean η_{mean} for different levels of each complexity factor, a) self-control, b) redundancy, and c) repeatability.

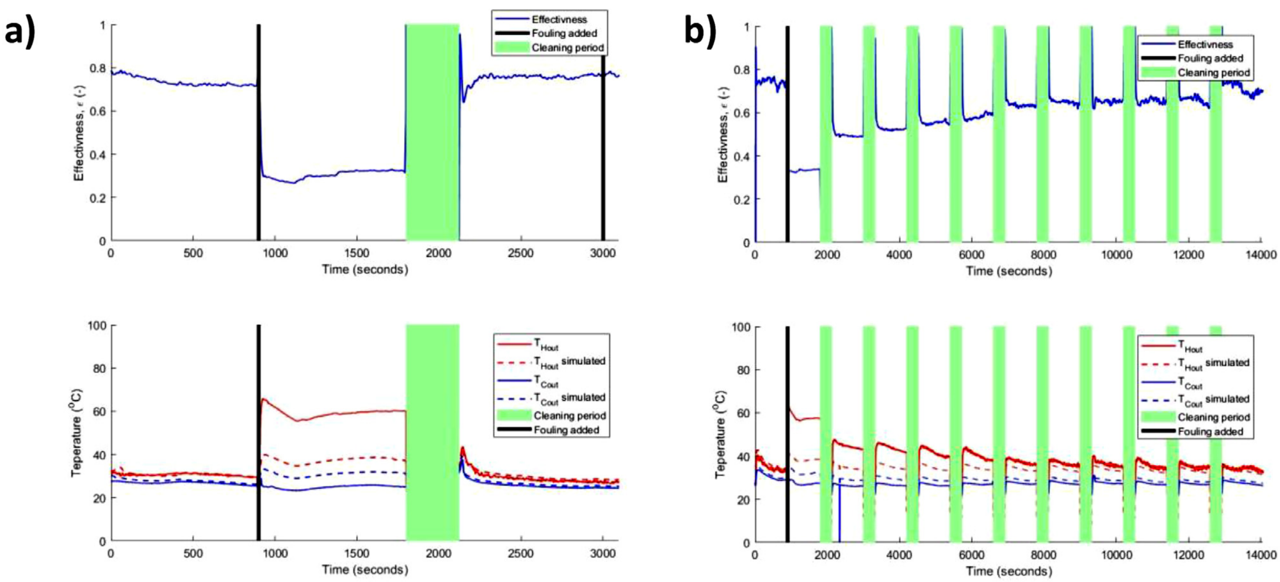

Fig. 13. Graphs or results with a) best and b) worst complexity levels. Experiments were run until $E_{SC} \geq 0.9$ was achieved. Top shows ε against time while bottom shows the temperature recorded and predicted by the DT for hot and cold HX outlets.

increased the impact of changing redundancy and made it more influential than self-control. However, in these experiments, the max flow was limited by the flow delivered from the mains water supply.

3.3.3. Repeatability

Changing the number of cycles has the smallest impact on E_{SC} of the three factors. The current SC setup was designed to be used for many cycles and to have a high level of possible repeatability. It would be expected that the performance for one, three and seven cleaning cycles would be similar because the HX is cleaned, and new fouling is added between each cleaning cycle. However, Fig 12 c) shows that cleaning after three cycles appears to be the best while experiments with one cleaning cycle are the worst, followed by seven. The variation in results could be due to ageing of a thin layer of fouling deposit which is not removed by the brush cleaning [6]; however, experiments cycles are conducted on the same day leaving little time for ageing of fouling. A thin film could be left at the end of each fouling-cleaning cycle which is not removed fully and impacts the next cycle. By the third cleaning cycles this layer could be larger and easier to remove than in the first cleaning cycle, leading to this difference in performance. Previous studies have shown that fouling build-up and cleaning performance can change with repeated cleaning-fouling cycles [55,56], though the reasons why can be difficult to identify and result from surface-fouling interaction.

The foam balls used are likely to become degraded over time as they are used; some could even become stuck in the HX. This would lead to faster degradation of the SC systems than just using pulses which only rely on one motorised valve to operate.

3.4. Further validation experiments

To validate the best and worst settings identified, a final set of experiments was performed. The best and worst complexity levels identified were compared. Previous experiments were stopped after 900 seconds, either for good or for more fouling to be added. However, these experiments were allowed to SC repeatedly until

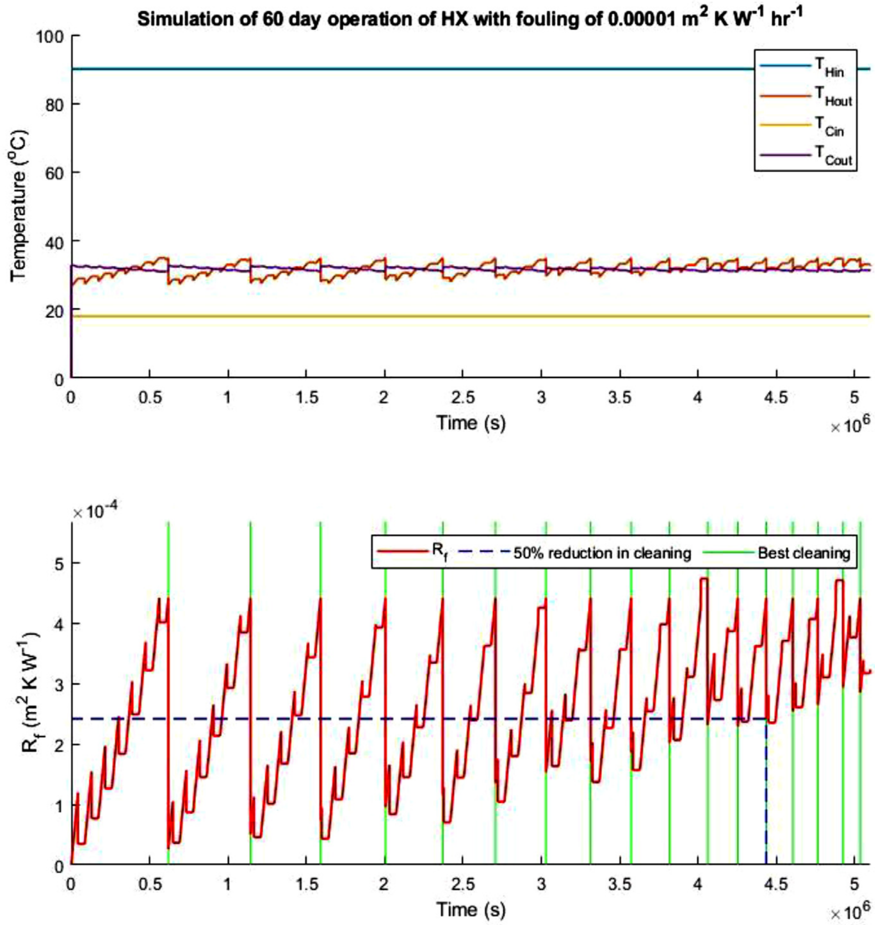

Fig. 14. Graphs or 60 days of 12 hour operation of the HX. Daily cleaning is performed with pulses and a better ball and pulse cleaning response is triggered when the temperature rises above 35°C. Top graph: temperature readings; bottom graph: fouling. A blue dashed line shows where cleaning effectiveness has reduced by 50% of original. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 6
Results of repeated experiments with best and worst complexity settings used. The ϵ_{Clean}, ϵ_{End} and E_{SC} and M_W values are shown for each experiment.

Settings	E_{SC}	Number of cleaning cycles	M_W
Best	0.99	1	57 kg
Best	0.94	1	57 kg
Best	0.96	1	57 kg
Worst	0.92	7	170 kg
Worst	0.92	10	243 kg
Worst	0.90	11	267 kg

90% of the original function was returned (when $E_{SC} \geq 0.9$). The controller used can be seen in Fig. 7; if fouling is registered over the following 900 seconds after cleaning, another cleaning cycle is triggered. This continues until $E_{SC} \geq 0.9$ is achieved Fig. 13. shows the results of two experiments conducted for the best (Fig. 13 a)) and worst complexity levels (Fig. 13 b)) Table 6. outlines all results from the experiments. Up to 10 more cleaning cycles are needed with the worst settings to meet the required cleaning standard. The total water used (M_W) is also estimated based on valve opening times; significant water savings can be made by utilising higher complexity levels. The worst complexity levels use a low flow rate but require more repetition resulting in high water use for cleaning overall.

3.5. Stopping SC criteria

Despite regular SC, the performance of the SC mechanism is unlikely to be effective forever. Either the SC mechanism performance can degrade or fouling deposits could age and become harder to clean. Eventually, the SC system would have to stop, and human intervention will be needed to clean and inspect the HX. This is difficult to test in experiments because it will require long term operation of the system. Instead, a HX simulation was created to model extended performance and demonstrate possible stopping criteria. Eqs. (1)–(5) were used to model the predicted output temperature of wort cooled from 90°C with 18°C water. Flow rates are kept the same as those used in the experiment ($\dot{m}_H = 0.035$ kg s^{-1}, $\dot{m}_C$= 0.15 kg s^{-1}). During the long term simulation, a linear fouling of 0.00001 m^{2}KW^{-1}h^{-1} [57] is applied, which reduces the heat transfer. This value of fouling increase is taken from wort boiling, not cooling, because no value could be found for cooling.

The simulation runs the HX for 12 hours each 24 hours for 60 days; at the end of the 12 hours, a SC operation is triggered with high flow rate and pulses (with $E_{SC} = 0.71$ in Table 4). This is less effective than using balls and pulses together but is also less complex because no balls are used, which could become stuck in the HX or pipes. The amount of fouling still increases every day as the pulse cleaning leaves some fouling behind. When T_{Hout} goes above 35°C (a comfortable temperature for yeast when brewing) a more effective cleaning in triggered using the best settings identified (with an average $E_{SC} = 0.97$ in Table 6).

The fouling left after each SC ages and becomes harder to remove, and E_{SC} reduces for each cleaning cycle. In the simulation, the effectiveness of cleaning for daily cleaning cycle x is $E_{SC_{Daily}}(x)$, and is assumed to follow Eq. (10). Ball and pulse cleanings with the best effectiveness ($E_{SC_{Best}}(x)$) are less frequent, leaving more time for ageing and assumed to follow Eq. (11).

$$E_{SC_{Daily}}(x) = E_{SC}(0)^x = 0.71^x \tag{10}$$

$$E_{SC_{Best}}(x) = E_{SC}(0)^x = 0.97^x \tag{11}$$

The simulation results are shown in Fig. 14; the top graph shows the HX temperature inputs and outputs while the bottom graph shows the fouling. The temperatures and fouling are all paused during 12 hours of no operation. The daily SC can be seen by the drops in fouling every 12 hours. Larger intensive SC with pulses and balls is shown by the green lines.

In reality, modelling fouling and cleaning are more complex, but this simulation is just designed to show how the SC performance is likely to degrade over time, and that manual cleaning will eventually be required. The blue dotted line on the bottom graph of Fig. 14 shows when the effectiveness of cleaning has reduced to 50% of its original performance. This is an example of when the SC mechanism could stop operating and a manual clean be performed. Beyond this point, the system performance degrades, and SC begins to occur almost daily on top of daily cleaning. With industry 4.0 and connected systems, the SC control shares data with other systems to identify the optimal stopping point.

4. Conclusion

The SE complexity framework presented in [21] was used to design an SC HX system. Three different factors are used in the framework, repeatability, redundancy and self-control; for each factor, a high, medium and low level were designed. Two different cleaning mechanisms were tested, pulsated cleaning flow and ball cleaning. Balls were released halfway through cleaning and partially blocked certain HX tubes; this leads to a faster flow rate in other tubes aiding cleaning. It is theorised that the balls are drawn to cleaner pipes with less or no fouling and promote cleaning of other fouled tubes. However, this cannot be validated in this study.

The number of experiments was reduced by using Taguchi's orthogonal array, with SC effectiveness values (E_{SC}) were optimised. Values of E_{SC} calculated from temperature were validated by comparing them to the number of pipes still fouled after each cleaning cycle. Evaluation of the results highlighted the best and worst levels for each complexity factor. The optimum cleaning was with pulses and balls, a flow rate of 0.21 kg s^{-1} of water, and three cleaning cycles. The worst cleaning used pulses, a flow rate of 0.09 kg s^{-1} and one cleaning cycle. These levels were validated in further experiments where the best design cleaned fouling in one cycle and returns at least 94% of pre-fouling performance. This is highly effective but needs to be tested on fouling in an industry HX. A longer simulation demonstrated how performance is likely to degrade over time and how a stopping criterion for the SC system could be identified by observing when the performance had reduced by 50%.

Changing the cleaning mechanism (self-control) had the biggest impact on performance, followed by changing flow rate (redundancy). Self-control was the most influential factor for this design, but this does not mean it will be for all SC systems or other SE systems. The design method used here could be useful for the design of other SE systems and help ensure effectiveness is maximised with minimal complexity. Currently only cold water is used in the experiments, but the cleaning fluid could be changed to hot water or chemicals, as used in existing CIP systems, to improve cleaning further. Future research should also focus on adapting this system for other types of HX, such as plate HX, which would not be suitable for the ball cleaning method used here.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Rajkumar Roy reports financial support was provided by Engineering and Physical Sciences Research Council.

CRediT authorship contribution statement

Sam Brooks: Investigation, Formal analysis, Writing – original draft, Conceptualization, Data curation, Methodology. **Rajkumar Roy:** Writing – review & editing, Methodology, Funding acquisition, Supervision.

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