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A B S T R A C T

This paper describes research efforts to improve the operation of industrial scale crisp fryers to ensure that product quality targets are exceeded. The work described was undertaken within a project whose aim is to minimise the acrylamide formation arising during processing operations. The existing fryer temperature control scheme was found to be sub-optimal from an acrylamide perspective and involved considerable operator intervention, particularly at fryer start-up. A new temperature control system was designed and implemented to overcome the shortcomings of the existing strategy. Fryer temperature and crisp moisture were regulated effectively through gas flow and dwell time modifications. Interactions between loops were compensated for and start-up was automated to reduce the impact of operator-to-operator variation. The resulting scheme was found to deliver much-improved temperature control which will lead to a resultant decrease in acrylamide formation.

1. Introduction

The need to minimise as far as possible the concentration of acrylamide in food products has been stated by food regulatory authorities with increasing frequency. From initial concerns raised in 2002 (Tareke et al., 2002) to stringent guidelines released recently (Commission Regulation (EU) 2017/2158), the onus is on manufacturers to follow the ALARA (As Low As Reasonably Achievable) principle. Interesting assessments are presented by Powers et al. (2021) of the success of this policy where evidence of long-term trends in acrylamide content of crisps indicate considerable reductions in the period 2002–2012 but little further reduction in subsequent years. Acrylamide arises as a by-product of the

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Maillard reaction and is formed when foods high in carbohydrates and a nitrogen source such as amino acids are cooked at a high temperature. If conditions in the frying of crisps are not tightly controlled, it can result in higher than desirable levels of acrylamide. The benchmark level of concern for acrylamide in crisps is set at 750 µg/kg and actions to achieve levels below this are described by Powers et al. (2021) and Mesias et al. (2019). Krishnakumar and Visvanathan (2014) and more recently Nematollahi et al. (2021) provide reviews that summarise the formation mechanisms in detail and the mitigation measures for a range of food products. Recent research has considered product pretreatment and coating before deep-fat frying for chicken based products (Jouki et al., 2021; Jouki and Khazaei, 2022). Medeiros Vinci et al. (2012) provide a detailed review concentrating on potato-based products. In their concluding comments they discuss the importance of the blanching operation and the effective control of the frying process. They state that '*it is necessary to improve the reliability and accuracy of temperature controls on frying equipment*'. That is the purpose of this study.

The two key unit operations that impact on the crisp quality are blanching and subsequent frying (Medeiros Vinci et al., 2012). With regard to acrylamide formation, the blanching operation is undertaken to lower the levels of reducing sugars in the potato slices before they enter the fryer. Lowering the reducing sugars ultimately leads to a reduction of acrylamide formation in the fryer. Studies on the impact of blanching of potato strips and slices by Mestdagh et al. (2008), Mariotti et al. (2015) and Palermo et al. (2016) described the importance of selecting the best blanching temperature and residence time. A detailed study on the blanching operation prior to the fryer considered in this paper is presented by Bartlett et al. (2020) and it has been optimised for maximum sugar removal effectiveness. While many factors impact on effectiveness, a reduction of around 50% of reducing sugars is typically achieved in the blanching operation.

Following blanching, the potato slices enter the fryer. The flow rate of potatoes down the line is approximately 3 tonnes/hour. High oleic sunflower oil is used in the fryer and the volume of oil present in the fryer is 6 m^3. Generic details of the operation of industrial-scale continuous fryers can be found in Wu et al. (2013a). In their study, they established a mathematical model for the fryer behaviour and estimated the temperature profiles experienced by the crisp during its passage through the fryer. Considering the link to acrylamide, early work by Williams (2005) demonstrated the importance of establishing a temperature profile in a continuous fry from 170 °C at inlet to around 150 °C at the exit to minimise acrylamide formation while maintaining product quality. From an operational control perspective, Wu et al. (2013b) built a model of a continuous industrial fryer and claimed a potential 10% energy savings with improved control compared to the standard operation of the fryer. Considering the influence of frying on acrylamide production, Gökmen et al. (2006) considered the impact of frying temperatures on french fries. They found that acrylamide formation was unacceptably high when moisture was low and the temperature of frying was between 170 °C to 190 °C with results at 150 °C producing relatively little acrylamide. Thus, tight temperature control at around 150 °C is indicated.

One of the options to radically reduce the acrylamide content of crisps is to employ vacuum frying. Belkova et al. (2018) found a 98% reduction in acrylamide levels in crisps that had been vacuum fried at 125 °C rather than normal frying at 165 °C. While clearly this is an appealing technology, our paper describes work on a large industrial manufacturing plant where such options are not feasible in the short term. There are further implications of the industrial applications nature of this study that constrain the breadth of possible improvements through the limitations of commercial reality. Potato variety selection and tuber reducing sugar content are a prime industrial focus and are subject to continuous improvement. While the specific varieties used are commercially confidential, the operating policy needs to be sufficiently adept at dealing with variety change throughout the year and as supply availability dictates. Typical potato varieties are early cropping varieties like Lady Rosetta and main crop varieties like Lady Claire which are better suited to longer term storage until use. There is also the risk mitigation of using a number of varieties so that if there is a problem like disease or extreme weather, there is more chance of ongoing supply. Selectivity will in the long term cause the acrylamide concentrations to reduce but natural variations and disturbances exist and therefore a control strategy as described is still necessary to reduce peaks as far as possible. Challenges still exist, for example with raw potato variations acting as a disturbance to control systems but the study does not seek to minimise reducing sugar concentrations in the potatoes. Other impacts such as those resulting from different frying oils could impact acrylamide concentration but are also beyond the focus of this study. The paper restricts itself to the temperature control improvements possible on a large-scale manufacturing plant and this is the specific aim of this study but recognising this is a component of a broader industrial improvement strategy.

This paper firstly considers the existing fryer control strategy and through consideration of historical process data, highlights the need for improved process control and steadier process operation. The need to remove variation at fryer start-up is demonstrated from historical performance and the effectiveness of an automated start-up control system is presented. Subsequently, the control strategy for continuous operation is considered and the improved functionality is demonstrated.

2. Materials and methods

The study described involved the analysis of industrial manufacturing line operation, consideration of the control system structure and how it could be improved, followed by the implementation of the enhanced control system to assess its effectiveness.

For a control system improvement study, the first step in the methods is to understand the control system and the performance of the process. Industrial measurements from the line were taken every minute and stored in the company manufacturing plant database. These were accessible for download and analysis. Discussions with plant engineers revealed the structure of the existing control strategy as discussed in Section 2.1. With an understanding of control system structure, online data retrieved from the plant data base provided indications of performance as discussed in Section 2.2.

2.1. *Existing fryer control strategy and consequences*

The existing fryer control scheme are shown in Fig. 1. Here it can be seen that the inlet temperature of the oil is controlled by variation of the oil heater gas flow. The operators set the

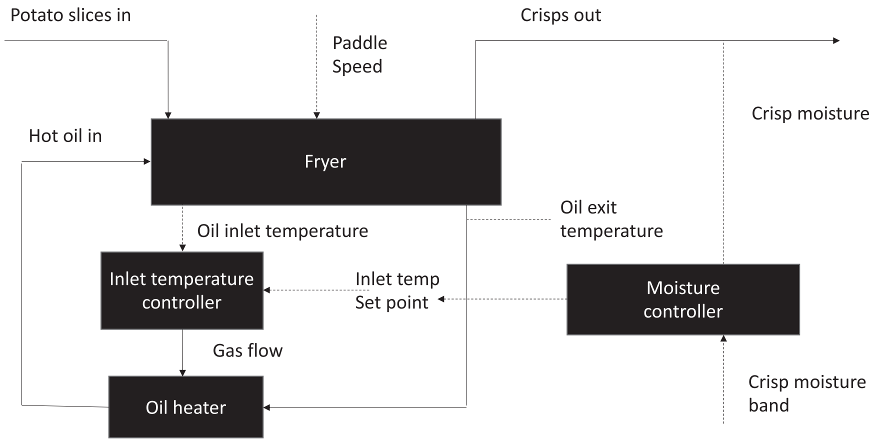

Fig. 1 – Existing fryer control system where the multiple control objectives of exit moisture and inlet oil temperature are controlled by a single manipulated variable (oil heater).

inlet temperature set point and rely on the design of the fryer to achieve the desired exit temperature and the design temperature difference across the fryer. The operators are also required to control the crisp moisture which is measured online with an infra-red probe after the fryer. The accuracy of this measurement can be expected to be ± 0.1% (Kress-Rogers & Brimelow, 2001). Crisp moisture is influenced by paddle speed (that sets the crisp residence time in the fryer) and fryer temperature profile. The operators predominantly left the paddle speed fixed and used the fryer inlet temperature to control the exit crisp moisture through manual intervention.

A fundamental flaw with the control scheme is that one manipulated variable (gas flow) is being used to achieve the desired inlet temperature and at that the same time to satisfy moisture constraints. This is not going to effective. Given the need to reassess the strategy, considering the design of an effective control scheme, several fundamental system aspects must be examined:

2.1.1. *What are the critical process variables to be controlled?*

The existing control scheme is set up to regulate fryer inlet temperature and the fryer exit temperature is not considered critical and consequently varies more than if it was controlled. It is known that acrylamide is formed when the moisture content of the crisp is low (Serpen and Gökmen, 2009, Wu et al., 2013a) which occurs at the exit of the fryer. Evaporation of water in the crisps keeps the crisp surface temperature low at the fryer inlet and only rises when the moisture at the surface is reduced towards the exit of the fryer. Thus, fryer exit temperature is more important to control than fryer inlet temperature. Furthermore, experience has shown (Gökmen et al., 2006) that a rapid rise in acrylamide formation occurs as fry temperature rises so a balance must be achieved between having a product that is sufficiently fried but not at too high a temperature to result in excessive acrylamide formation. For the product of interest, the exit temperature was specified to not exceed 154 °C, with a target exit temperature set point of 152 °C (consistent with the observations of Gökmen et al. (2006)). This temperature was found to minimise acrylamide formation and also result in high-quality fried crisps. It is also crucial that crisp moisture is controlled within specification. Thus, both fryer exit temperature and crisp moisture must be controlled.

2.1.2. *What control 'handles' can be manipulated and are there less than the number of critical process variables?*

Given that the operators predominantly fix the fryer residence time and use the fryer inlet temperature set point to adjust moisture, essentially two output variables (crisp fry through exposure to appropriate fryer temperature profile and moisture) are being controlled by the inlet fryer temperature set point. Two outputs cannot be controlled independently by a single manipulated variable. Thus, the control scheme needs to utilise the residence time in the fryer as well as the fryer gas rate as manipulated variables.

2.1.3. *Where do disturbances to steady state operation arise and how can their impact be minimised?*

Considering line operation, disturbances to steady state operation arise from process stops and starts, line speed changes, potato load changes and unit deviations upstream of the fryer. All will act to disrupt steady state operation. While some operational changes can be made to reduce the severity and impact of disturbances, it is nevertheless inevitable that disturbances will occur. From a control design perspective, supplementing feedback control systems with feedforward to reduce loop interaction and preempt the impact of disturbances on quality variables needs to be considered.

2.2. *Historical performance assessment*

The fryer under consideration processes 3 tonnes/hour of potatoes and has a residence time of around 8 min. The availability of minutely logged process data from 2017 onwards allowed an assessment to be made of the effectiveness of the original temperature control scheme and to gain more insight into line performance. In considering the information available online, it is important to be cognisant of the measurement characteristics and the accuracy and consistency of the information that is logged. A comprehensive consideration of typical measurement characteristics in food manufacturing operations can be found in Kress-Rogers & Brimelow (2001) and the process measurements logged have similar accuracy characteristics. Temperature measurement via thermocouples has an accuracy of around ± 0.5 °C. Given the temperature variations experienced, such accuracy limits are small compared to process change and do not impact on performance assessment. Fig. 2 shows the fryer inlet and exit oil temperatures from a random day in the period 2017/2018

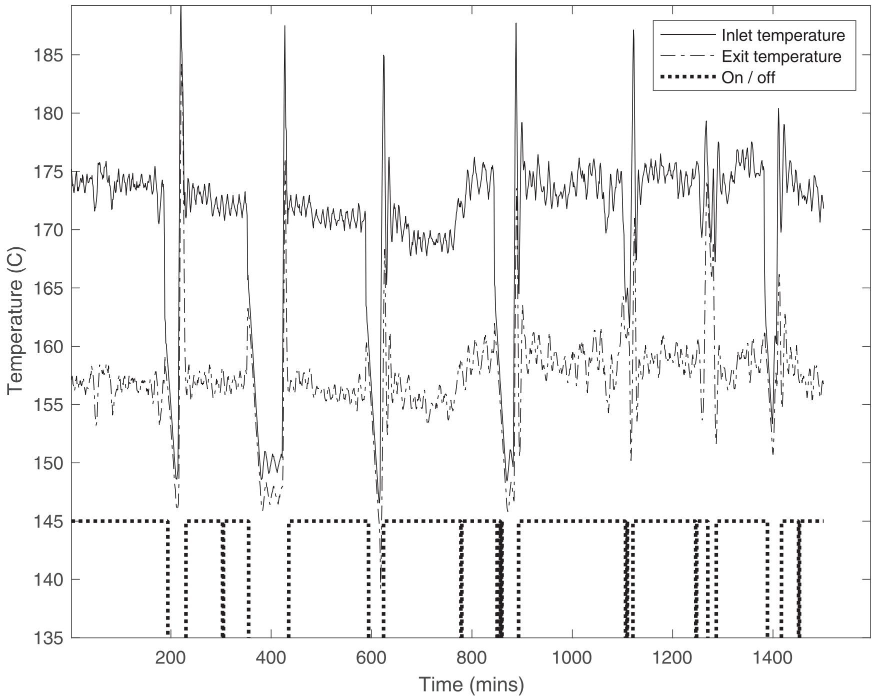

Fig. 2 – Typical daily temperature profile of inlet and outlet fryer oil indicating frequent stop / starts and a predominance of higher than desirable fryer exit temperature.

during which the fryer temperatures measured by thermocouples are under reasonable control. The lower step like dotted line shows when the production line is on or off and the temperatures can be seen to fall when the line is switched off.

Without focusing on the finer detail of the dynamic response, it can be seen that the fryer exit temperature is predominantly over the 154 °C operating constraint while the line is on. A number of line start / stops are clear throughout the day causing disturbance to steady operation at each instance.

Considering the finer detail, the dynamics in Fig. 2 are expanded in Fig. 3 showing the inlet temperature and the inlet temperature controller set point. During normal operation, Fig. 3 shows the exit temperature oscillating between approximately 152 °C and 165 °C with a mean of around 158 °C. To achieve normal operation, operators start-up the fryer and bring it to frying temperature. This can be

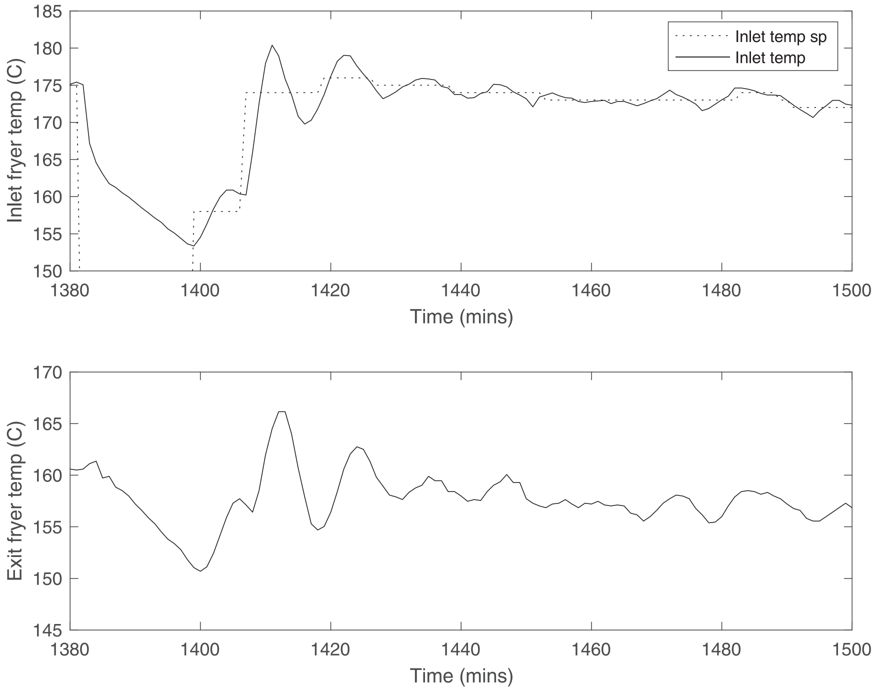

Fig. 3 – Dynamic response at start-up of fryer demonstrating inlet temperature overshoot of setpoint and the value of setpoint set too high so that higher than desirable exit temperature results.

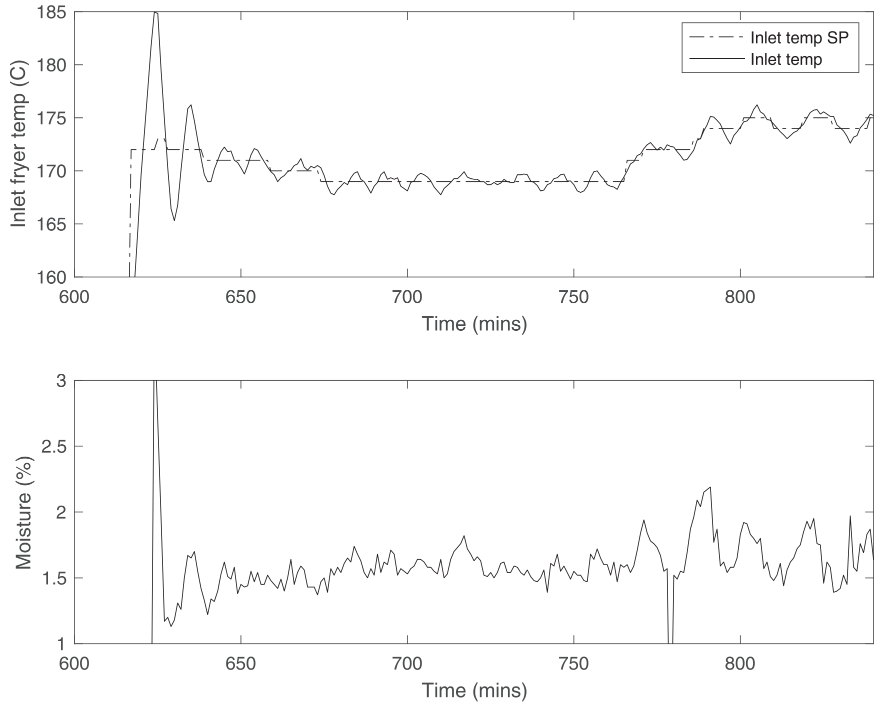

Fig. 4 – Moisture control via fryer inlet temperature set point (SP) demonstrating how, with moisture content increasing, fryer temperature is increased by the operators, with likely impact on acrylamide formation.

seen at around 1400 mins. Short time-period increases in inlet temperature set point around 1420 mins are initiated by the operator as the prevailing belief was that this would ensure faster progression to steady state operation. No standard operation policy existed for start-ups and such decisions were made on an individual operator basis. In this case, the oscillations subside after around 30 min but much longer periods of oscillation or severe overshoots are commonly observed. Fig. 4 demonstrates that the inlet oil temperature reaches 185 °C for example. If steady state operation was maintained for a long period following a line stop, such a relatively short period of oscillation could be tolerable, but with multiple stops per day (as seen in Fig. 2), oscillation becomes a frequent characteristic.

What is clear from these observations is that control performance of fryer outlet temperature is mixed in effectiveness and when it is poor can result in exit temperatures of 10 °C over the desired exit temperature. Given the temperature effect on the rate of reaction to produce acrylamide, a 10 °C increase could lead to around 50% increase in acrylamide formation (Ledbetter et al., 2020).

In Fig. 4 it can be seen that the operators use the inlet fryer temperature to compensate for changes in crisp moisture. At around 770 mins the exit moisture rises above the upper limit of 2.1% and an increase in inlet temperature is implemented. This is repeated several more instances taking the inlet temperature to 5 °C above the previous steady state. Such changes are typical when a potato load change introduces unfried slices with higher moisture content. The impact of this on exit moisture is noteworthy. In the period between 670 and 770 mins the exit temperature is around 155 °C but it rises to a mean of 160 °C as a result of the moisture control changes. This is significantly higher than is desirable for low acrylamide production. During this time, the fryer residence time is kept constant and not used as a control variable.

Finally, as the start-up is left in the manual control of the operators, it is interesting to consider if they carry out the task differently and with varying effectiveness. If the fryer has been stopped for a relatively short time and temperatures have not fallen significantly from normal operating levels then starting with the steady state temperature set point is effective. However, if the temperature has fallen significantly the operator's preferences influence behaviour. Data from line start-ups was gathered and Fig. 5 shows performance that is characteristic of observed behaviour. In Fig. 5a it can be seen that the operators take the inlet temperature to a steady state set point (SP) in two moves, leaving time for the response of the first move to impact. Resultingly the overshoot of steady state inlet temperature is small. Minor changes in inlet setpoint at around 20 min are made as steady state conditions become established. This is characteristic of a good start-up. Fig. 5b shows a more problematic start-up where fryer exit temperature is above ideal. A rapid move to an inlet temperature setpoint at the steady state value causes considerable temperature overshoot. The higher than desirable outlet temperature is caused by the inlet temperature being set to be too high. If stops/starts were infrequent this would not necessarily be so problematic but Fig. 2 shows that stop/starts are commonplace and therefore start-up control needs to be more effective than this.

Analysis of the historical data reveals four key features:

a) Control of moisture and fryer temperature need to be decoupled so that control changes for moisture do not impact on fryer temperature.
b) The control of fryer temperature needs to switch to exit temperature if acrylamide control is to be improved.

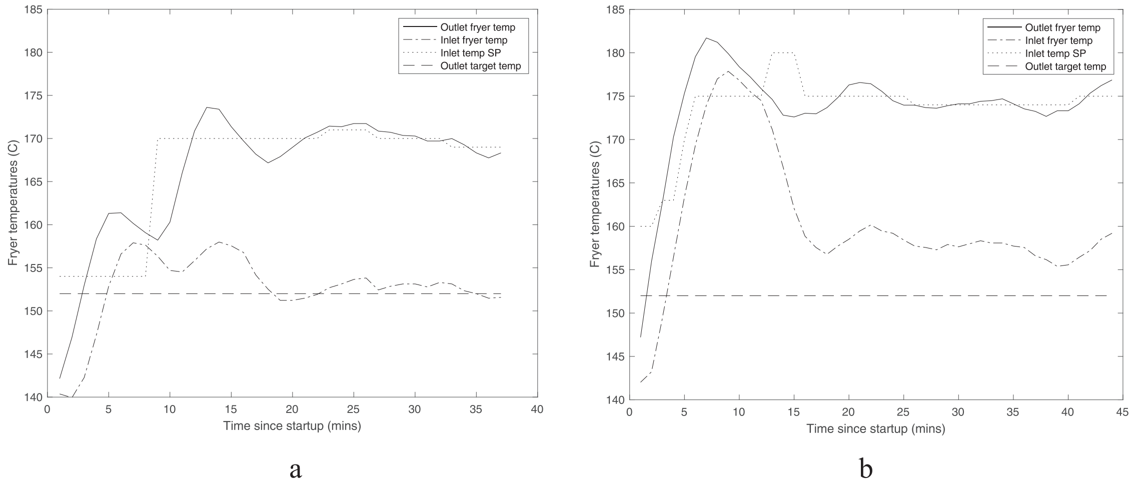

Fig. 5 – a – Fryer start-up example 1 with low overshoot and good adherence to outlet temperature target. b – Fryer start-up example 2 with significant overshoot and poor adherence to the outlet temperature target.

c) Increases in fryer inlet temperature over that required for steady state operation to 'prepare' for the addition of potato slices needs to be improved. Rather than allowing operators to take manual and different actions, an automated approach for start-up is required.
d) Line starts cause disruption to 'steady state' operation. The number of start-stops per day needs to be reduced if steadier line operation is to be achieved.

The paper sets out the fryer control improvements to address the first three of these improvements. Mechanical line changes have been undertaken to address the fourth aspect and are beyond the scope of this paper but have been responsible for a significant reduction in start-stops.

3. Results and discussion

Results from control system improvements cover the start-up of the fryer and the regulation of temperatures in continuous operation. Pre and post improvement results and statistics capturing performance are provided to indicate the improvements attained.

3.1. *Improved fryer start-up*

The above data suggests that fryer start-up is a major cause of temperature deviation from steady state operation. Data observation indicates that some operators are more adept at starting the fryer than others. Factory data from over two years of operation was available to investigate the best approach to take but to do so requires a definition of what constitutes 'best'. A balance is necessary between rapidly bringing the fryer online to produce a product and avoiding temperature overshoot which is consequence of a rapid rise in fryer temperature as this results in high acrylamide. The initial strategy developed replicates the action of the operators who avoid temperature overshoots by implementing large temperature set point changes when distant from the steady state operating point and these become smaller changes as it is approached. Set point change magnitudes and wait times were varied to bring the fryer online most rapidly without overshooting. An example of one of the first trials is shown in Fig. 6. Here for the trial, inlet temperature control was maintained rather than switching to outlet temperature control. The key objective was to demonstrate that temperature rise to a steady state was sufficiently short and no temperature oscillations occurred. Here it can be seen the temperature rise takes less than 20 min although this depends on the starting temperature which results from natural cooling.

The results in Fig. 6 were generated as part of initial trials where manual setpoint changes were made. Following several such trials a flow-chart of the scheme was developed and implemented in the fryer programable logic control. In the final start-up scheme, initial large increases in temperature were replaced by a steady increase of 4 °C per minute until the operating temperature is achieved. This was found to reduce the chances of overshoot and provide a good transition to steady state operation. An example of its behaviour can be seen in Fig. 7 where overshoot is minimal. Consequently, the start-up policy becomes automated and removes operator to operator differences.

3.2. *An improved continuous operation control strategy*

The first stage in improving the control system was to move to one where moisture is controlled via paddle speed in the fryer (thus setting residence time) and fryer exit temperature is controlled by gas supply to the fryer. This would have the effect of ensuring excessive exit temperature does not arise at the position in the fryer where most acrylamide is formed while still regulating moisture. The advantage of controlling fryer inlet rather than outlet temperature is that at start-up the response when cold potato slices fall into the fryer is immediate but if outlet temperature control is utilised then a large delay before they arrive at the outlet would result and a big temperature deviation would occur. To circumvent this the scheme in Fig. 8 is implemented where inlet temperature control is used until the initial flow of crisps arrives at the exit and then the control system switches over to outlet temperature control.

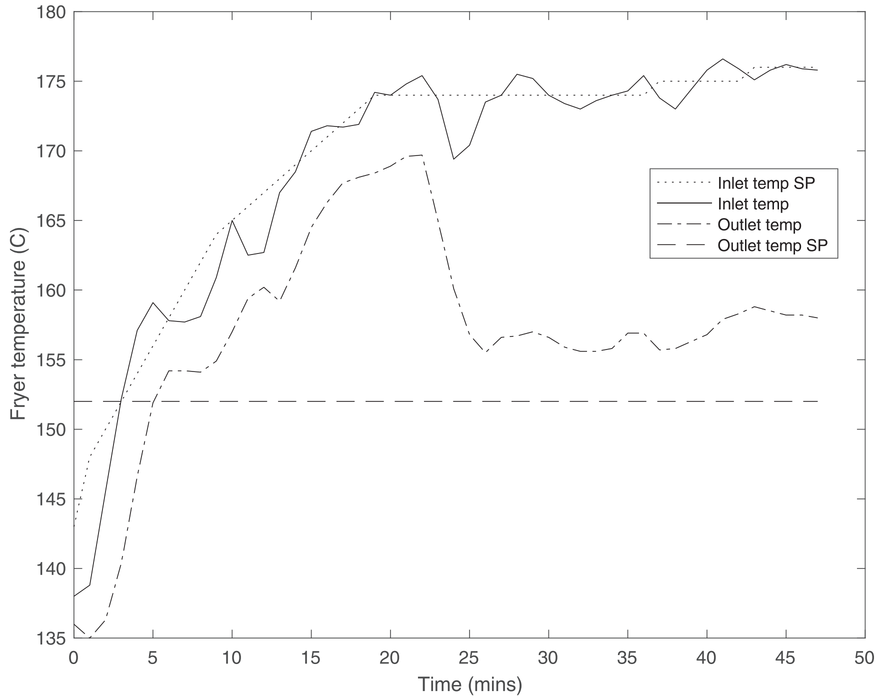

Fig. 6 – Initial trial of the automated start-up procedure carried out by manually changing setpoints (SP) following the first iteration of a prespecified procedure.

The control scheme in Fig. 8 was implemented and the performance measured over a month of operation is summarised in Table 1. As there are four process lines, it is possible to compare behaviour of the new control scheme with that of the existing control scheme. In Table 1 MIMO (multi-input multi-output) refers to the control scheme shown in Fig. 8 and SISO (single-input single-output) refers to the control scheme in Fig. 1. MC is the percentage moisture content of the crisps and acrylamide load score (ALS) is determined by the reaction rate / temperature relationship in Fig. 5b in Ledbetter et al. (2020) and is given by:

$$ALS = 0.00005\,\exp^{0.0641\times Outlet\ Temperature} \quad (1)$$

where the Fryer outlet temperature is in centigrade and the parameters were determined by curve fitting to the reaction rate / temperature relationship. This serves to penalise high

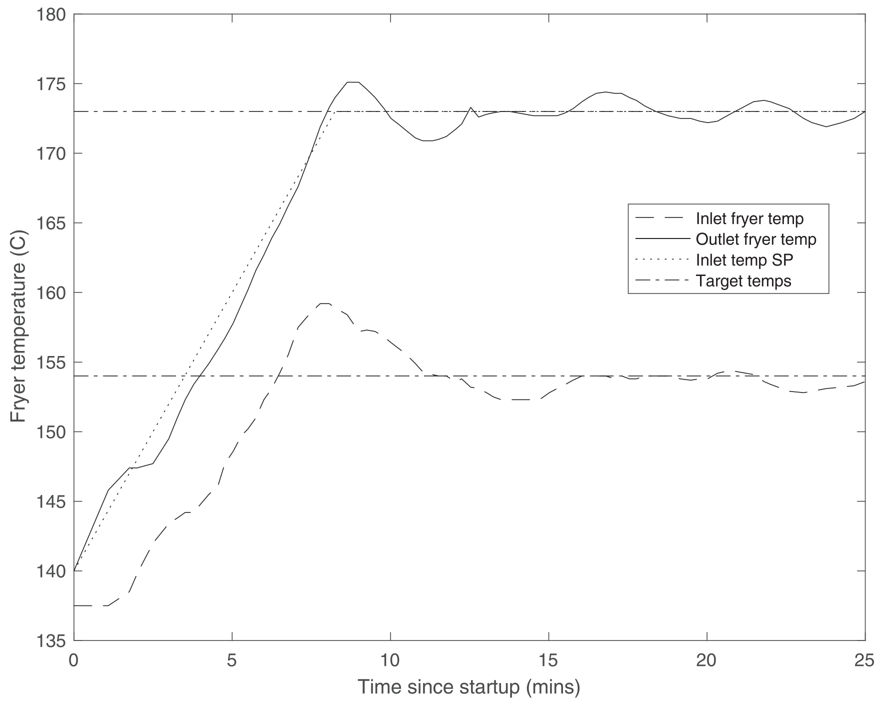

Fig. 7 – Automated start-up behaviour demonstrating that with careful choice of slope of setpoint increase, a good start-up can be achieved without overshoot and with good adherence to the ideal exit fryer temperature target.

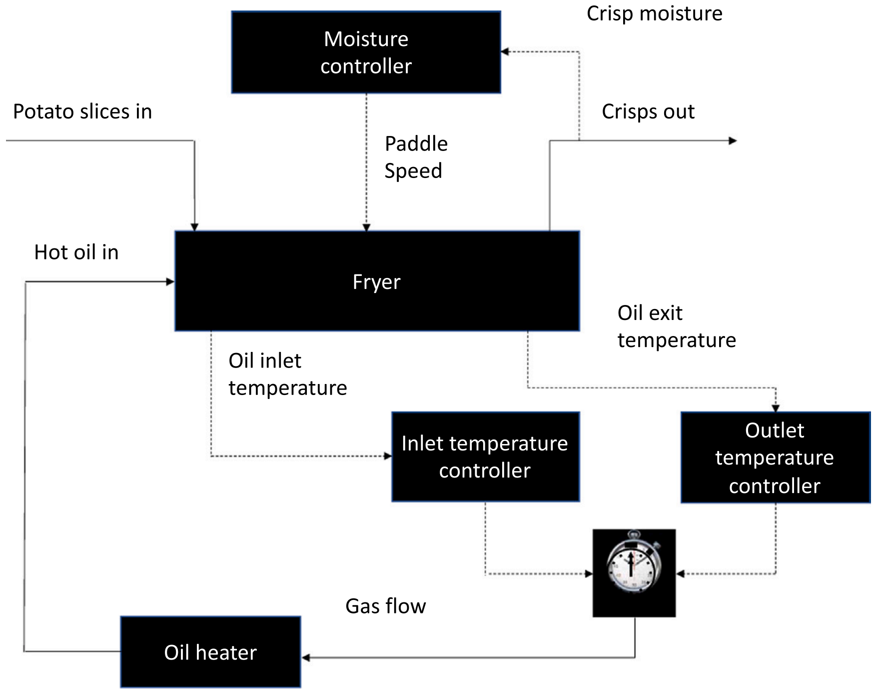

Fig. 8 – Improved control scheme for the fryer adopting a multi-input multioutput control strategy.

Table 1 – Control performance assessment of Single input-Single output (SISO) and Multi input-Multi output (MIMO) control schemes.

Control Scheme	SISO	MIMO
Operation (mins)	18,942	21,606
Time exit temp < 154 °C (mins)	3564	20,406
Time exit temp > 154 °C (mins)	15,378	1200
Mean ALS	1.13	0.76
Time MC < 1.8%	67.5%	48.1%
Time MC > 2.1%	4.8%	12.5%
Time MC 1.8–2.1%	27.6%	36.9%

temperature excursions with more weight as they would lead to higher rates of acrylamide formation. The statistical curve fitting and subsequent statistical analysis described below was undertaken using Matlab from Mathworks (Release R2021b).

In Table 1 the time the fryer spends with an exit temperature above 154 °C is determined. While 152 °C is the set point / target temperature, 154 °C is the upper control limit that is flagged to the operator as a concern and requiring action. For the MIMO scheme the fryer remains under the 154 °C limit for 94.4% of the time while this is only achieved for 18.8% for the SISO scheme. Where the MIMO fails to achieve the temperature target is associated with start-ups and a refined start-up procedure is described in Section 4. These results precede the implementation of the automated start-up strategy. The ALS value is calculated from the predominant rate limiting step in acrylamide production which is the rate of reaction of asparagine and fructose to acrylamide as outlined in Ledbetter et al. (2020). The motivation is that rather than using temperature deviation as a metric of performance, adopting a nonlinear weighting for the error-based deviation (founded on the reaction rate relationship with temperature) more heavily penalises high-temperature deviations as these lead to high relative accumulations of acrylamide. Thus, the ALS metric is a surrogate measure of propensity to form acrylamide. Such an approach would be in keeping with the reaction mechanisms and acrylamide formation models proposed by Knight et al. (2021).

Moisture content has a target range of 1.8–2.1% with hard limits of unacceptable product above 2.5%. This hard limit does not exist below 1.8% but such a product is more susceptible to failing quality assurance checks. Moisture content above 2.5% is only associated with start-up and improved control of this is discussed in Section 4. The control performance with the original scheme can be seen to result in a higher percentage of over-dry crisps. Apart from quality issues, over-dry crisps are not desirable as crisps are sold by weight and therefore over-drying results in a yield reduction and energy are required to over-dry and is therefore wasted. When the process variable standard deviation is large due to poor control and a hard constraint exists, the tendency by operators is to set the mean operating level some way from the hard constraint (and wasted product) and here this results in a significant amount of product MC below the lower desired level. With improved control the mean operating MC can be increased as the standard deviation is reduced while retaining the same probability of violating the higher constraint. The MC figures in Table 1 show this effect and Fig. 10 below gives a perspective on this over one day's typical operation.

Considering the behaviour in more detail for a typical day, Fig. 9 shows the ALS values and Fig. 10 the MC. Improved temperature control results in more consistent and lower ALS values (MIMO) compared to the previous control strategy (SISO). The standard deviation of the MC value can also be seen to reduce. Temperature spikes and MC values over 2.5% are at the early stages of fryer start-up and the latter stages

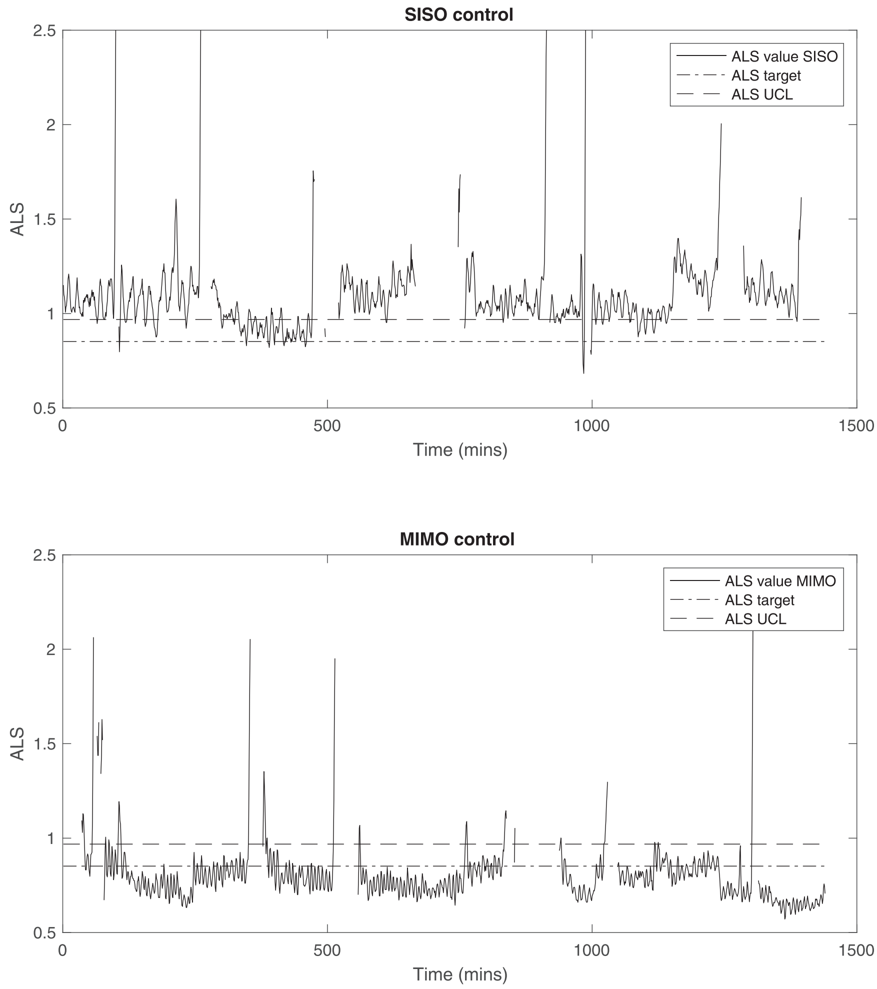

Fig. 9 – Single input – Single output (SISO) and Multi input -Multi output (MIMO) ALS comparison for a typical days operation demonstrating operation closer to target for the MIMO scheme.

of shutdown. Note that crisps are not exposed to these temperature extremes.

In considering moisture behaviour, it is important to be aware of the likely sensor accuracy of ± 0.1% (Kress-Rogers & Brimelow, 2001) and thus high frequency variation (0–100 mins in the SISO plot for example) should not be considered indicators of process change but trends to 1.5% and above 2.1% are indicative of deviation. Thus, the UCL (upper control limit) at 2.1% is specified to give a sufficient margin that the operators can respond to deviation and avoid violating the unacceptable product constraint at 2.5% given the probe accuracy. The exploitation and implementation of such information in a food processing environment from a statistical process control perspective is described in Lim et al. (2014).

3.3. *Dashboard development*

At the commencement of the study, while fryer data was logged on a minute basis, it was not easily accessible or routinely viewed by staff responsible for the management of the operation. As the focus on acrylamide became greater, attention to the detailed operation of all units in the production intensified. With previous studies on the washing stage described in Bartlett et al. (2020) being effective, observations of acrylamide concentration revealed that with lowered reducing sugars, it was still possible to get high acrylamide by frying incorrectly. Attention therefore focused on the fryer control to a much greater extent and also addressed the needs of a management information system. The studies described above focused on the details of individual dynamic responses, that level of detail is not required from a management perspective. Thus, to support the control improvements, a simple fryer performance dashboard was developed, pulling data from the data historian and providing simple daily and weekly metrics that summarised adherence to the target operation such as percentage time fryer exit temperature greater than constraint and error metrics that are typical in control loop performance assessment but weighted by the exponentially by the extent of deviation to account for nonlinear acrylamide reaction kinetics as in the ALS metric above. Prior to this study fryer data was not easily accessible to management, an Excel spreadsheet on their desktop PC now facilitates much better oversight of performance and increases observed in metrics can be investigated further.

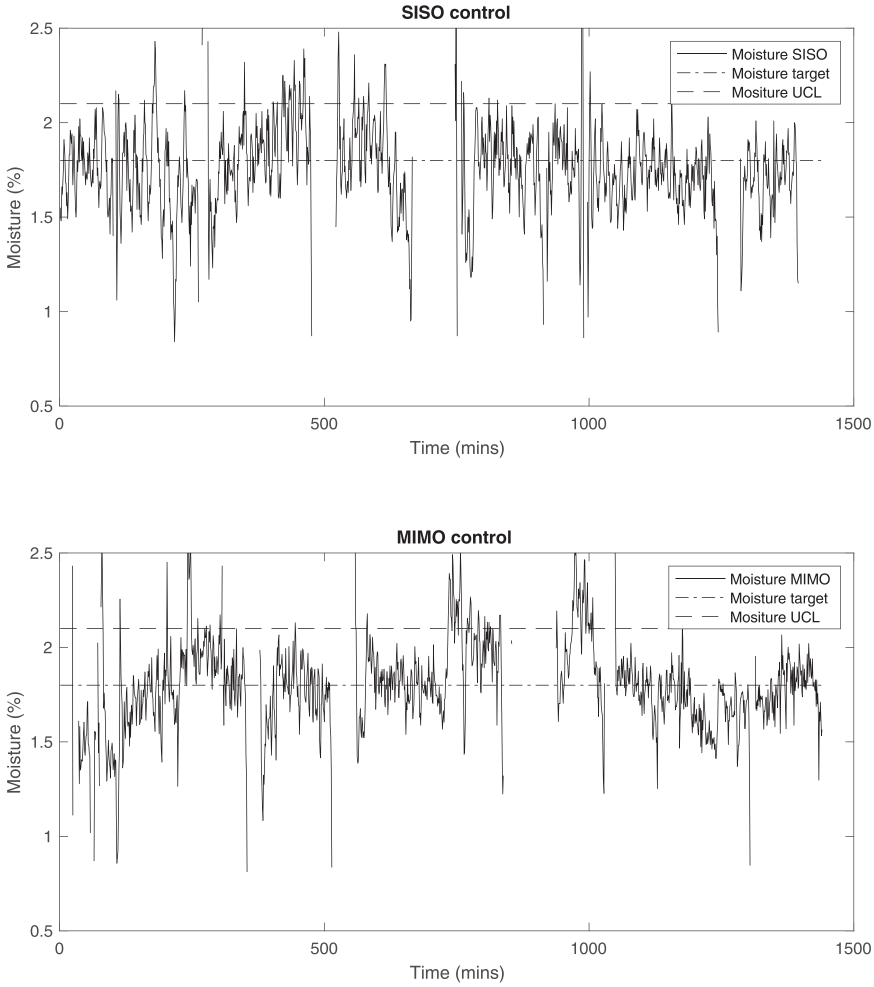

Fig. 10 – SISO & MIMO MC comparison for a typical days operation demonstrating improvements in moisture control from the MIMO scheme.

4. Concluding comments

In drawing conclusions from this study, the predominant considerations are: (i) the effectiveness of the alternative control strategy, (ii) the appropriateness of conventional control within the strategy rather than using more sophisticated algorithms, (iii) the information required to be provided to those responsible for managing the new control system and crucially, (iv) has the product quality been positively influenced by the control system changes.

In considering the appropriateness of the existing control scheme, a prime consideration is the key quality attributes and the 'handles' that are available to control them. In this paper, the increasing need to satisfy acrylamide concentration constraints has re-prioritised the key quality attributes for the fryer and thus led to changes in the control system employed. Previously, given the responsiveness of the inlet temperature to start-up and line speed changes, inlet fryer temperature control was understandably considered to be preferable. However, given that acrylamide production occurs when the crisp moisture is low at the end of the fryer, it follows that if reduction in acrylamide concentration is to be prioritised then outlet temperature control is preferable to post fryer start-up. This paper has demonstrated that the exit temperature control scheme can be established to give improved acrylamide control, while at the same time ensuring other product quality attributes are also satisfied. For example, no statistically significant variation in oil uptake by the product was observed.

Regarding seeking more sophisticated control system approaches, a temptation might have been to turn to more 'advanced' control strategies, such as adopting a model based predictive controller without thorough justification. This paper has demonstrated that the performance obtained with the improved conventional scheme suggests that the 'keep it simple' principle negates the adoption of a predictive controller, with acceptable behaviour attained with improved conventional design. No doubt a predictive controller would have been effective from a performance perspective but hardware/software costs, maintenance challenges and limited additional benefits are prohibitive concerns.

Considering information provision, an important aspect of the control improvement was the development of a control system performance dashboard for production management use. While it is not sophisticated, prior to the study their awareness of fryer dynamic performance was limited as data access was problematic. A simple Excel spreadsheet available on their PC and accessing the data historian calculates metrics summarising performance and has vastly improved oversight.

Finally, with regard to product quality, given the objective of the study is to reduce acrylamide concentration, the ideal control system would measure it directly rather than the approach adopted here of controlling temperature which is linked to acrylamide formation. The activity described in this paper is part of a larger project where measurement options are considered but measurement development has focused on rapid at-line analysis. While mention was made of methods such as NIR or colour to determine acrylamide concentration as online approaches, as the limits have become stricter, the capabilities required to achieve the lower levels are not present. Offline sample analysis remains how to validate control effectiveness. Samples are expensive to analyse and the industrial strategy of daily measurement does not align with control system dynamic behaviour assessment from an acrylamide perspective. However, given the undeniable link between high fryer exit temperature and high acrylamide, the scheme demonstrated offers good assurance of low acrylamide levels. The validation by measurement of acrylamide throughout several seasons of crop will ultimately verify the benefits.

Overall, concentrating on a specific industrial scale manufacturing line, the paper has demonstrated the postulated control system design is effective for this case. Product quality, as measured by the conventional metrics for crisps, has been maintained and the likely acrylamide content reduced. Considering the broader scope, the fryer design is commonly found and the nature of the frying challenge arises for many products, thus the approach postulated is likely to be directly transferable to other continuous frying lines.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Phil Green, Industrial Technology Systems; Malcolm Knott, Industrial Technology Systems; Stan Higgins, Industrial Technology Systems; Karen Stott, Industrial Technology Systems; Ged McNamara, KP Snacks; Ben Davies, KP Snacks; Alberto Fiore, University of Abertay; Keith Sturrock, University of Abertay; Moira Ledbetter, University of Abertay; Ingo Hein, James Hutton Institute; Sophie Mantelin, James Hutton Institute; Brian Harrower, James Hutton Institute; Gary Montague, Teesside University.

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