

Risk Assessment of Subcritical Water Hydrolysis (SWH) System for Sugar Recovery using Failure Modes and Effects Analysis (FMEA) Methods

(Penilaian Risiko Sistem Hidrolisis Air Subkritikal (SWH) untuk Pemulihan Gula menggunakan Kaedah Mod Kegagalan dan Analisis Kesan (FMEA))

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ABSTRACT

The subcritical water hydrolysis (SWH) process has proven to be an effective method for sugar recovery from bakery waste. However, the natural principle of the process involving high pressure and temperature has made it a hazardous operation. Hence, failure mode and effect analysis (FMEA) has been applied to identify the potential failure modes in subcritical water hydrolysis (SWH) systems. The Risk Priority Number (RPN) approach was used to rate each potential problem during the SWH process. The reactor unit was found to have the highest potential for failure by RPN value of 800 with the 'failure effect analysis' on the potential reactor cap to explode due to the very high pressure inside the reactor that developed during SWH. The failure consequences may lead to injury or even death. As a result of the FMEA assessment approach and several corrective action plans, the failure risks of SWH can be reduced and managed effectively.

Keywords: Failure mode and effects analysis (FMEA); food; Risk Priority Number (RPN) Continuous Improvement (CI); safety; subcritical water hydrolysis (SWH)

ABSTRAK

Proses hidrolisis air subkritikal (SWH) telah terbukti sebagai kaedah yang berkesan untuk pemulihan gula daripada sisa bakeri. Walau bagaimanapun, prinsip semula jadi proses yang melibatkan tekanan dan suhu tinggi telah menjadikannya operasi yang berbahaya. Oleh itu, analisis mod dan kesan kegagalan (FMEA) telah digunakan untuk mengenal pasti mod kegagalan yang berpotensi dalam sistem hidrolisis air subkritikal (SWH). Pendekatan Nombor Keutamaan Risiko (RPN) digunakan untuk menilai setiap masalah yang berpotensi semasa proses SWH. Unit reaktor didapati mempunyai potensi kegagalan yang paling tinggi dengan nilai RPN 800 dengan 'analisis kesan kegagalan' pada penutup reaktor berpotensi meletup kerana tekanan yang sangat tinggi di dalam reaktor yang berkembang semasa SWH. Akibat daripada kegagalan boleh membawa kepada kecederaan atau kematian. Hasil daripada pendekatan penilaian FMEA dan beberapa pelan tindakan pembetulan, risiko kegagalan SWH dapat dikurangkan dan diuruskan dengan berkesan.

Kata kunci: Hidrolisis air subkritikal (SWH); keselamatan; makanan; mod kegagalan dan analisis kesan (FMEA); Nombor Keutamaan Risiko (RPN) Penambahbaikan Berterusan (CI)

INTRODUCTION

Continuous Improvement (CI) holds various definitions related to continual improvement or continuous innovation. CI is not a recent technology as it has been an important part of manufacturing since the stone age, where humans were continuously looking for a better way to do their jobs or improve their tools. Bhuiyan and Baghel (2005) stated that in the early 1900s, scientific management has emerged and started developing methods to assist the managers in analyzing and solving production problems using scientific methods.

Vinodh and Chintha (2011) explained that productive systems have evolved from the craft manufacturing era, where all the products were handmade, to the mass manufacturing era, where the manufacturing systems repetitively produced the same products but in mass productions. Then followed by the emergence of Lean Manufacturing (LM), where the focus has shifted to waste elimination, thereby achieving cost reduction.

Caroly et al. (2010) summarized CI as the continuous improvement process that aims to optimize information, physical flows, and products to control production costs and quality. Despite the variety of CI definitions, the most important thing is that the organizations have to apply it and show evidence of their practice in quality audits. The principle of CI is often referred to as vital for organizations as it is based on the ISO 9000:2000 series of standards but has a different meaning according to different authors (Sousa 2007).

There are several tools to facilitate CI, such as Plan-Do-Study-Act (PDSA) also known as Deming Cycle, Kaizen, Lean Six Sigma (LSS), Lean Manufacturing (LM), and Total Quality Management (TQM). One of the most common methods employed is Failure Mode Effect Analysis (FMEA). FMEA is a proactive method to prevent system failures instead of an after-the-fact analysis method. FMEA is not only used to assist CI, but FMEA is also one of the reliability management tool techniques commonly utilized to guarantee the security and reliability of the systems, services, and projects (Huang et al. 2020). The goal of reliability analysis is to measure and analyze the system failures to reduce or eliminate their likelihood and safety risk (Ebeling 2004). Thus, FMEA is an effective approach and a strong core in terms of CI, reliability, safety, and quality improvement.

Balmforth et al. (2003) explained how an insufficient hazard identification method is to blame for the failure to detect, prevent, and minimize losses. The initial step

in risk analysis is hazard identification, which seeks to identify all probable sources, conditions, or acts ahead of time. Fires, explosions, and environmental destruction can result from this type of devastation. Inadequate danger identification might occur due to incorrect application instruments for hazard identification or the incorrect use of the correct tools.

Mhetre and Dhake (2012) mentioned that Failure Mode Effect Analysis (FMEA) is employed to identify all failure modes of different parts of the system, the effect of these failure modes on the system, and how to circumvent the failure and/or moderate the effect of the failure system. FMEA is a step-by-step tactic to identify all possible failures throughout the process, while 'Effect Analysis' means analyzing the consequences of those failures. It was first developed and implemented back in 1949 by US Army and was later executed in the Apollo space program (Carlson 2014). The 'effects' analysis looks at how a failure affects the system, the people, and the environment. This could be the discovery of top-level or multi-level effects. There may be multiple effects for each failure mode, but the FMEA team normally focuses on the effect with the most serious impact on the study (Hassan et al. 2022).

The main purpose of FMEA was to connect links between causes and effects of defects and search, solve and draw the best decisions regarding solicitation of appropriate action. FMEA was also an effective method in engineering design, production process, and new product in planning (Parsana & Patel 2014). A successful FMEA analysis can identify potential failure modes based on experiences with related products/processes/problems, allowing the management team to design those failures out of the system with minimum efforts and resource, thereby reducing the time and cost (Shinde et al. 2015).

FMEA is still currently being widely employed in various areas, such as the mining industry (Balaraju et al. 2020), passenger vehicle recalls (Chi et al. 2020), oral multi-unit pellet formulation (Patel et al. 2022), lyophilized parenteral products (Poms et al. 2019), water treatment plants (Gheibi et al. 2019), metal printing (Peeters et al. 2018), and temperature sensor (Catelani et al. 2018). However, very limited studies have been reported on utilizing FMEA in the food industry, and to the best of author's knowledge, no study using FMEA has been done on subcritical water treatment systems.

The subcritical water hydrolysis process is an eco-friendly treatment that uses the unique properties of subcritical water that is water above its boiling point

(100 °C, 0.1MPa) to high temperature-pressure conditions below its critical point (374 °C, 22 MPa) (Essien et al. 2020). Because of its advantages of being a green extraction approach, providing higher quality extraction products, and being cost-effective with a short extraction/treatment time as compared to the traditional method, there is an expanding number of literature on subcritical water treatment (Du et al. 2019; Imteaz & Shanableh 2004; Wiboonsirikul et al. 2015).

Several studies have reported on the success of utilizing subcritical water in recovering sugars from various sources, such as bakery leftovers (Mohd Thani et al. 2020a), orange peel (Lachos-Perez et al. 2020), pecan waste (Santos et al. 2020), coconut husk (Muharja et al. 2020), mangroves (Pangestuti et al. 2020), sago bark (Amin et al. 2020), and algae (Greiserman et al. 2019).

Several factors affected the efficiency of subcritical water; temperature, pressure, time, solid-to-water ratio, the particle size of raw materials, pH, and addition of other materials such as surfactant and catalyst. However, temperature plays the biggest influence on the overall competence of the process (Mohd Thani et al. 2020b). The subcritical water hydrolysis process can be conducted in three systems, batch system (where the reaction took place in the reactor), semi-batch system (samples are contacted with a continuous flow of subcritical water), and lastly continuous system (both samples and

subcritical water continuously entering and exiting the reactor) (Lachos-Perez et al. 2017).

Subcritical water treatment operated under high temperature and pressure conditions, which this process is exposed to an extremely high probability of safety issues, mainly an explosion could happen. The University of Hong Kong reported an explosion in 2010 involving a vessel used in the hydrothermal process. Hau (2010) reported that the explosion could be caused by overheating the hydrothermal vessel. It is crucial to carry out FMEA so that further safety measurements can be taken to ensure low risk. Therefore, this study aims is to conduct an FMEA analysis on a batch subcritical water treatment system for sugar recovery from bakery waste.

MATERIALS AND METHODS

SUBCRITICAL WATER TREATMENT (SWT)

SWT was executed in a batch-type oil bath reactor (Thomas Kagaku Co. Ltd) for temperature range 100 - 200 °C, and a batch-type salt bath reactor (Thermometer Inspecting Bath TIB-450-16L) for temperature range 220 °C - 374 °C, fitted with heating coils and type -K thermocouple to regulate temperature (Figure 1). The orthographic view of assembled subcritical water salt bath reactor with its components is presented in Figure 2. For the oil bath reactor, silicone oil was used, while for

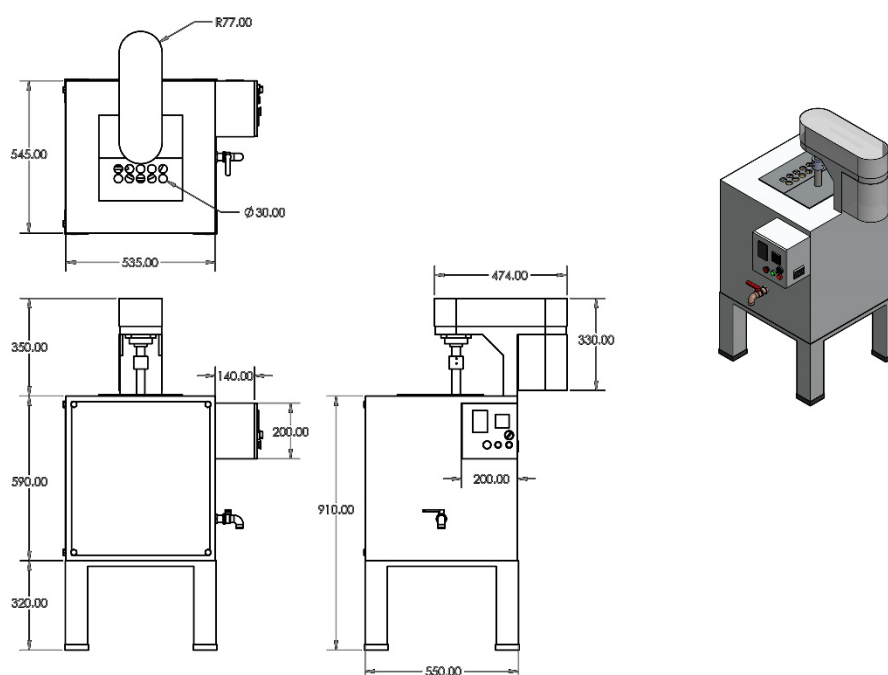


FIGURE 1. Subcritical water salt bath reactor with dimensions

the salt bath reactor, a ratio of 1:1 of potassium nitrate salt and sodium nitrate salt was applied.

The reactors (Figure 3) were a high-pressure-resistant vessel made from stainless steel (Diameter cap: 2 cm, Length: 17 cm) Swagelok, Malaysia. In this study, two types of bakery leftovers were chosen as raw materials; doughnuts and croissants. The bakery products (doughnuts and croissants) were left in an air-tight container at room temperature for two days, ground using a knife mill, and later ready to be used as raw materials for subcritical water hydrolysis.

The reactor was inserted with raw materials at different solid-to-water ratios. Then, Argon gas was used to purge the reactor for about 3 min to release the air

trapped in the reactor. Next, the reactor lid was clamped tightly. The reactor was then submerged in the oil/salt bath at a specific process temperature and process time. After the heating process, immediately cooled the reactor to stop the reaction by running tap water. Subsequently, the reactor was opened using a custom-made reactor opener (Figure 4). There were two points (top and bottom) to hold the reactor caps. The handle behind it would give enough pressure to the bottom cap to loosen the top cap. The summary of the overall setup of the subcritical water hydrolysis process is presented in Figure 5.

FAILURE-MODE-EFFECT-ANALYSIS (FMEA) PROCEDURE

FMEA started with specifying all the functions of an item, including the environment it has to operate. The

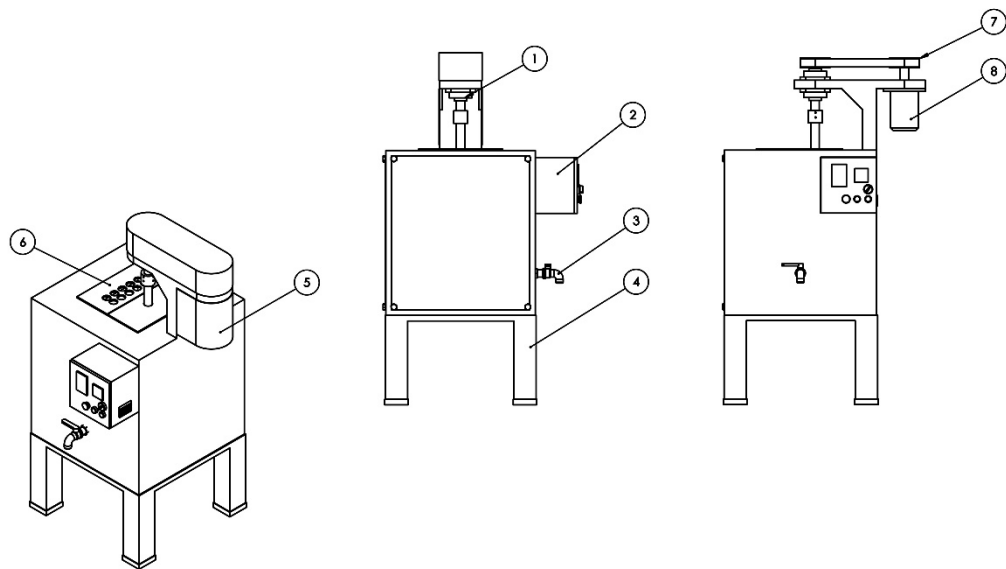


FIGURE 2. An orthographic view of assembled subcritical water salt bath reactor with its components (1. Stirring bearing; 2. Operational panel control box; 3. Discharge pipe; 4. Frame; 5. Heat cover; 6. Liquid tank top cover; 7. Belting; 8. Electric motor)

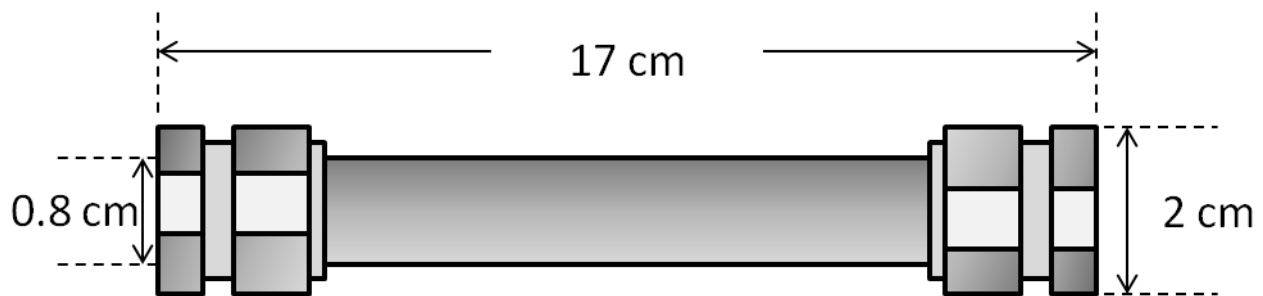


FIGURE 3. Schematic diagram of the stainless-steel reactor



FIGURE 4. The actual custom-made reactor opener (left) and the reactor opener with reactor placed in it (right)

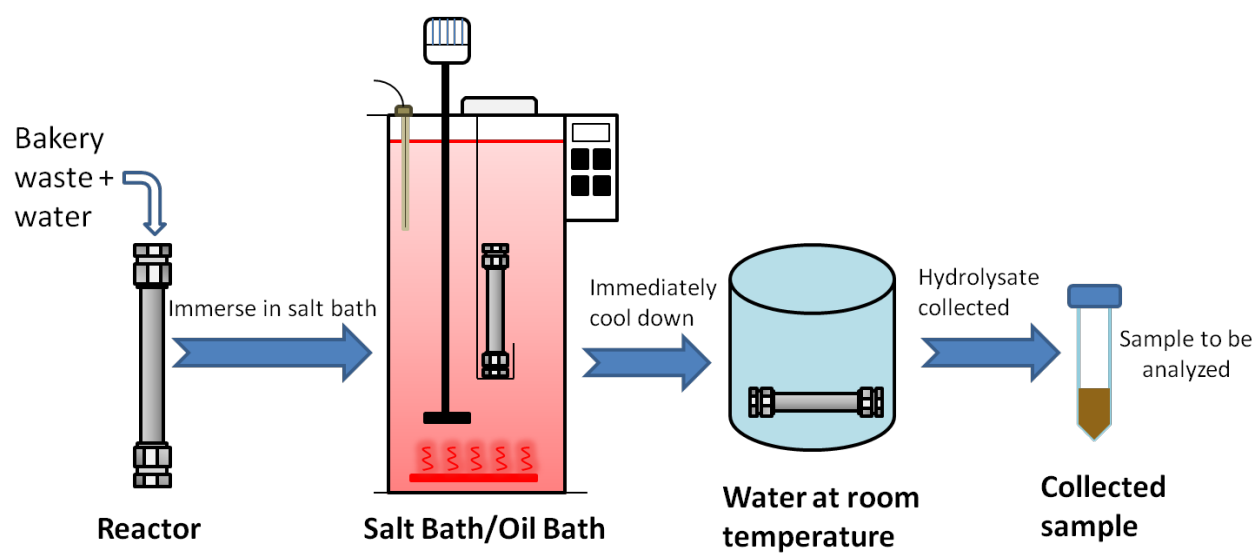


FIGURE 5. Schematic summary of the overall subcritical water hydrolysis process

next step was to identify the potential failure mode and potential effects of failure. All the past failures, present reports, and brainstorming meetings have been conducted in this step. From there, a severity report assessed the seriousness of the effect of the potential failure mode. The example of severity ranking is shown in Table 1 (Shinde et al. 2015).

After that, every cause and mechanism were listed concisely. Examples of 'failure causes' are incorrect material, poor environmental protection, and inadequate design. While examples of 'failure mechanisms' are fatigue, wear, corrosion, and yield. Next, identification the possibility of occurrence of each failure. Occurrence is the chance that one of the specific causes/mechanisms will occur. It is crucial to look at the cause of a failure and how many times it occurs by examining similar products or processes and the documented failures. An example of occurrence rating is presented in Table 2 (Parsana & Patel 2014).

After identifying the occurrence, the next step was detection, which was the relative measure of the ability of design control to detect whether a potential cause/mechanism or the subsequent failure mode before production. Table 3 displays the table of detection.

Subsequently, the Risk Priority Numbers (RPN) were calculated. RPN was the sign for determining proper corrective action on the failure modes. It was calculated by multiplying the severity, occurrence, and detection ranking levels resulting in a scale of 1 to 1000. Small RPN was always preferable to high RPN. It can be calculated for the entire process and/or for the process design only. After RPN was calculated, it was easy to determine the area of greatest concern, and the engineering team could focus on the solution of the failure modes. The equation of RPN was calculated as (Equation 1):

$$RPN = Severity \times Occurrence \times Detection \quad (1)$$

The overall FMEA procedure is summarized in Figure 6.

TABLE 1. Severity ranking

Effect	Criteria: Severity of effect on process (manufacturing/assembly effect)	Rank
Failure to meet safety and/or regulatory requirements	May endanger operator (machine or assembly) without warning	10
	May endanger operator (machine or assembly) with warning	9
Major disruption	100% of the product may have to be scrapped. Line shutdown or stop ship	8
Significant disruption	A portion of the production run may have to be scrapped. Deviation from the primary process including decreased line speed or added manpower	7
	100% of the production run may have to be reworked off-line and accepted	6
Moderate disruption	A portion of the production run may have to be reworked off-line and accepted	5
Moderate disruption	100% of production run may have to be reworked in-station before it is processed	4
	A portion of the production run may have to be reworked in-station before it is processed	3
Minor disruption	Slight inconvenience to process, operation, or operator	2
No effect	No discernible effect	1

TABLE 2. Table of occurrence and its code

Code	Classification	Example
10 & 9	Very high	Inevitable Failure
8 & 7	High	Repeated Failure
6 & 5	Moderate	Occasional Failure
4, 3 & 2	Low	Few Failure
1	Remote	Failure Unlikely

TABLE 3. Table of detection

Detection	Rank	Criteria
Extremely Likely	1	Can be corrected prior to prototype/controls will almost certainly detect
Very High Likelihood	2	Can be corrected prior to design release/very high probability of detection
High Likelihood	3	Likely to be corrected/High probability of detection
Moderately High Likelihood	4	Design controls are moderately effective
Medium Likelihood	5	Design controls have an even chance of working
Moderately Low Likelihood	6	Design controls may miss the problem
Low Likelihood	7	Design controls are likely to miss the problem
Very Low Likelihood	8	Design controls have a poor chance of detection
Very Low Likelihood	9	Unproven, unreliable design/poor chance for detection
Extremely Unlikely	10	No design technique available/controls will not detect

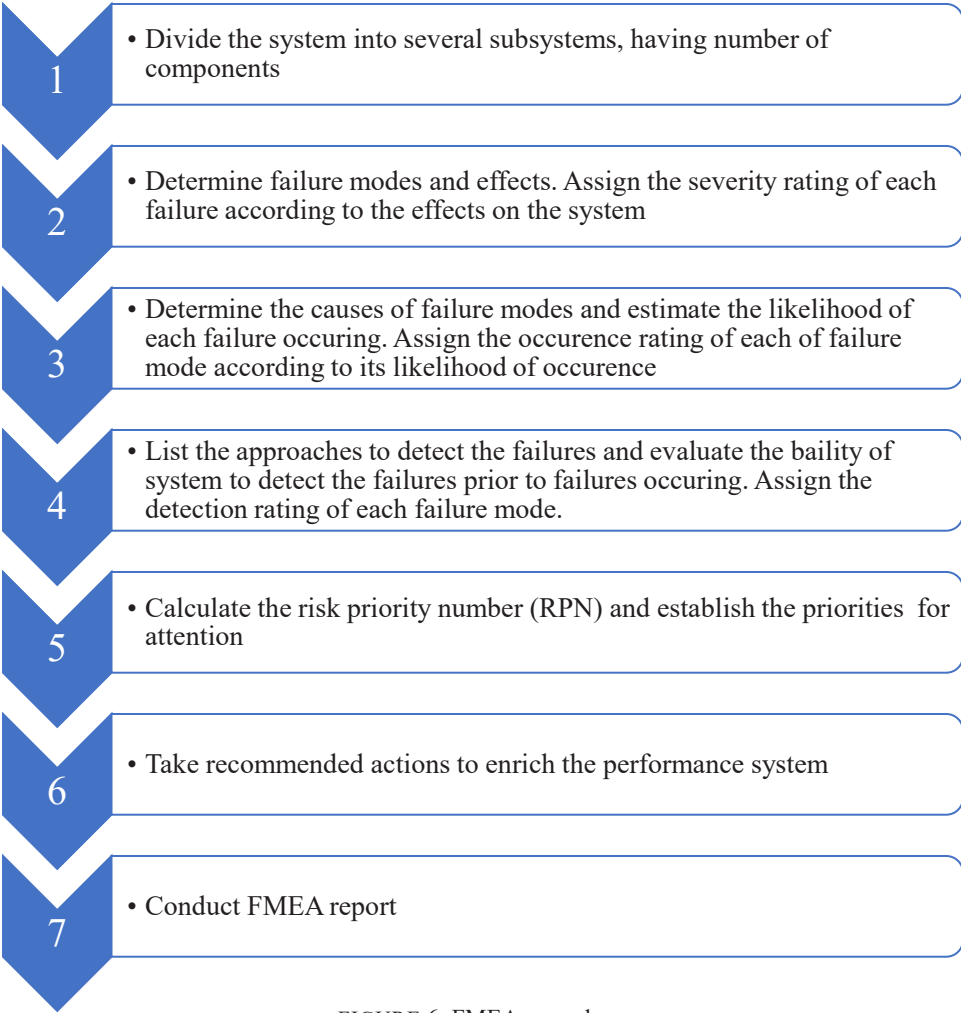


FIGURE 6. FMEA procedure

RESULTS AND DISCUSSION

FMEA OF SUBCRITICAL WATER TREATMENT

An FMEA has been conducted on the SWH process involving several important major units, starting from materials, material weighing, reactor, salt/oil bath, and

finally, the operators. The FMEA covered all the possible failures, their effects, causes, and consequences from the initial step of SWH until disassembling the reactor. The severity ranking (S), occurrence ranking (O) as well as detection (D) ranking were based on personal experience while doing the lab-scale SWH as well as experience. The FMEA report was presented in Table 4.

TABLE 4. FMEA of SWH

Unit/ Component	Failure Mode	Failure Effects	Severity (S)	Failure Causes	Occurrences (O)	Failure Consequences	Detection (D)	RPN	Recommended Action
Materials	Materials out of specification	Raw materials need to be discarded	8	In proper storage condition	6		2	96	Regular storage condition checking
				Raw materials have been spoiled/ contaminated	5		2	80	
		Water cannot be utilized		Water contamination	2	1) Loss in production time 2) Loss in income	2	32	Regular water quality maintenance
	Inaccessible	Water not available		Disruption of water supply	6		2	96	Installation of backup water supply
		Raw materials not available	7	Late arrival of raw materials	5		4	140	Regular checking on the number of raw materials
Material weighing	Error calibration	Different results from two device	8	The device is not calibrated well	4	1) Loss in yield 2) Loss in income	2	64	Regular device calibration
			7	No standard for material loss	4		4	112	Administrative prepare standard for material loss
Reactor	Damage	Disruption of water to achieve subcritical phase	9		8		7	504	Reactor replacement after certain cycles and ensure the reactor cap gap measuring tool usage.
		Inefficient pressure in the reactor	9		8	1) Loss in yield 2) Loss in production time 3) Loss in income	7	504	
		Water leaking into salt/oil bath	10	1)Error in reactor setup 2) Loose cap	8		8	640	
		Disruption of heat supply to the water	9		8		8	576	Scheduled reactor cap checking, replaced reactor after specific cycles.
	Unsuccessful assemble & disassemble	Cut or injury to the worker	9	Improper tools	9	1) Loss in production time 2) Minor injury	8	648	Design and select appropriate tools
		Potential reactor cap explodes	10	Very high pressure inside the reactor	10		8	800	Training on the effective and safe way of disassembling the reactor
		10	Cap was too tight	9		8	720		

Salt/oil bath	Explosions	Potential explosion and damage the entire working area	10	Unidentified material during the process	4		4	160	Check and clarify the materials that go inside the reactor
			10	The unstable temperature of equipment	3	Injury or death	4	120	Regular maintenance checking
			10	Low amount of salt/oil	8		4	320	
	Leakage	salt solution or oil leaking	9	Cracks in the wall of the salt/oil bath	2	1) Loss in production time 2) Minor injury	4	72	1) Regular maintenance checking
			9	Loose discharge valve	2		4	72	2) Salt/oil bath replacement
	Short circuited	Equipment downtime	7	Electricity supply	3	Loss in production time	2	42	Installation of backup generator
Operator	Personal Protective Equipment (PPE)	Exposure to high heat from salt/oil bath	7	Improper PPE	Minor or severe injury	9	630	1) Awareness and training on safety 2) PPE checking procedure before work	
		Potential contact with hot salt/oil sparks	8			10	9	720	
	Error	Inaccurate measuring of materials	8	Fatigue or out of focus	1) Loss in yield 2) Reworked	2	128	1) Awareness and training on weighing 2) Appropriate hours of working with sufficient rest	
		Incorrect equipment setup	9			8	2	144	

FAILURE AND IMPACT ANALYSIS

Based on Table 4, RPN is the Risk Priority Number representing failure that needed the most attention. This study noted that the 'reactor unit' has the highest RPN value, which indicates it has the highest possibility for failure. Therefore, utmost attention must be given to this unit. Regarding failure mode for reactor unit, 'damage' criteria have a high value of PRN (504- 640), while 'unsuccessful assembling & disassemble of the reactors' has higher severity with an RPN value of 648 -

800. In terms of failure effects analysis, 'cut or injury to the worker' and 'reactor cap exploded' are identified as possible effects while disassembling the reactor. These are based on personal experience and communication with other personnel that has conducted the subcritical water reactor.

In this study, the reactor (as the process vessel) was used extensively, high severity of failure could arise due to reactor damage. The reactor cap needed to be assembled and closed tightly prior to the SWH process

began, and later opened and disassembled after the SWH process was accomplished. The frequent procedure of assembling and disassembling the reactor may affect its efficiency, thus may cause water to leak from inside the reactor into the salt/oil bath. This effect could only be detected after the SWH process, where all the liquid inside the reactor dried out. This failure can result in a loss in yield, production time, and, most importantly, loss in income.

Furthermore, the second-highest RPN value (144 - 720) is arisen by the 'operator' unit. For this unit, failure due to personal protection equipment (PPE) is given a high RPN value of 630 to 720. The effects of failure are possible to derive from the 'exposure to high heat from

salt/oil bath' and 'potential contacts with hot sparks from salt solution or oil bath'. These failures might cause due to improper use of Personal Protective Equipment (PPE) that possibly results in minor or severe injury.

Salt/oil bath had few failures, which were severe but had low occurrence. The potential failures listed were explosions, leakage, and short-circuited due to the experience of an explosion that had the highest severity (10), caused by the presence of unidentified materials inside the reactor. Furthermore, other effects listed were potential explosions caused by unstable temperature and a low amount of salt/oil inside the salt/oil bath.

Finally, in the unit of materials and material weighing, the RPN calculated were slightly lower than



FIGURE 7. The safety cage for SWH with its components (1. Salt/oil bath; 2. Lock; 3. Standard operating procedures)

other units as the severity was not high and the detection procedures were very likely to work.

CORRECTIVE ACTION IMPLEMENTATION

After a thorough analysis of failures and their effects, developing a corrective action implementation plan is crucial. The corrective action plan proposed involved

the safety aspects of the working space, machines, instruments, and personnel.

In terms of working space, a safety cage (Figure 7) was built to place the salt/oil bath during SWH. The main function of the safety cage was to contain any salt solution or oil from spattering to the other areas in case of an explosion. The dimension of the cage was 5 ft × 5 ft × 7.22 ft, made from mild steel (inner frame) and

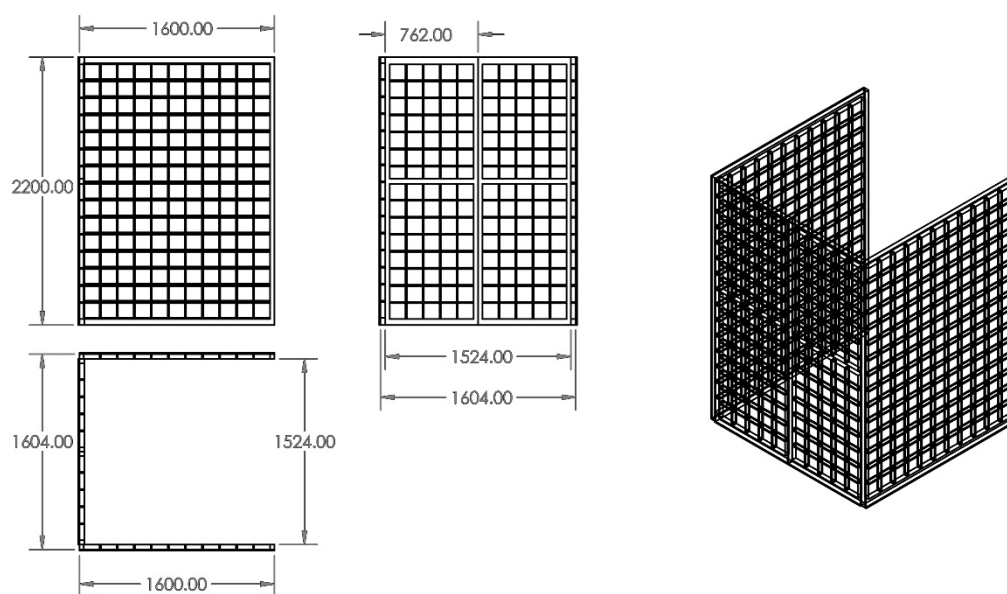


FIGURE 8. The safety cage for SWH with dimensions

acrylic (outer) (Figure 8). It was built with a front door, equipped with a lock for safety purposes.

It is decisive to schedule regular maintenance check-ups to ensure that all the equipment is in good condition when it comes to machines and instruments. Furthermore, appropriate tools selection and training with an effective way to handle the reactors may reduce the possible failure to happen.

Finally, as part of corrective action, schedule and proper training on various safety aspects must be carried out as an awareness. Personnel needs to be trained on PPE, safety measurements, and emergency response.

CONCLUSION

This work develops a safety assessment of the SWH process through the FMEA approach. This approach has identified some of the possible hazards and their severity. FMEA can be used as a safety assessment as

it provides detailed information on each of the units or components involved during the SWH process. Based on the FMEA report, the reactor has the highest RPN value, while materials and materials weighing has the lowest RPN value. Therefore, correction action plans have been recommended and should be implemented. FMEA has proved to be an effective tool in assessing the safety and reliability of the SWH process.

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