Original Article

HAZOP Analysis and Reliability Assessment of Closed Loop Solar Water Heater System for Residential Application

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ABSTRACT : *Solar thermal system or solar water heater system is one of the applications used to produce hot water in the residential sector. This paper describes HAZOP analysis and reliability assessment to evaluates the potential hazard and system probability for the closed loop solar thermal system applied for the residential area. Hazard identification for the main system components is analyzed while Fault Tree Analysis (FTA), Reliability Block Diagram (RBD) and Weibull distributions performed to determine the reliability for the overall system. The result shows that there are 49 potential hazards for the system with failure probability at 0.23822 and the reliability is 0.9693. Subsequently, this study determined the potential hazards for the system which can be anticipated by the residential consumer for the safety aspect. Furthermore, the evaluated reliability result shows that the application of closed loop type solar water heater system at residential premises is highly recommended due to its long lasting operational condition.*

Keywords – *HAZOP, Fault Tree Analysis, Reliability Block Diagram, Weilbull Distributions, Solar Water Heater*

1.0 INTRODUCTION

Solar thermal technology is widely applied in various sectors including residential, industry and commercial sectors for heating & cooling purposes. There are few types of solar thermal collector technology which is commercially applied depending on the temperature requirement. Solar thermal system can be divided into two types which is passive system (open loop) and active system (closed loop). For the passive system (thermosyphon and integral collector – storage system), it relies on natural convention to circulate the water and therefore the tank must be located higher than the collector panels. Meanwhile, for the active system (direct and indirect system), it utilizes pump to circulate the water between the tank and the collector (International Energy Agency, 2012). According to the literature study, it is found that a number of equipment failures for active system may occur in the solar thermal system such as the leaking of thermal storage tank, continuously develop stress in the system, collector defect, instability of the mounting structure, valve problem and pump failure. These technical issues from the equipment will possibly cause hazard towards the system and thus affecting the safety of users (Menicucci, 2009). Therefore, this paper will present the study on the HAZOP analysis and reliability assessment for the closed loop solar thermal system for water heating application at the residential area. Hazard and Operability study (HAZOP) is a qualitative method that used to identify and evaluate the initiating events (problem) that may represent risk to personnel or equipment or prevent efficient operation (Rausand, 2005). In this process, it requires to assess how big the potential risks involved where the management can focus their attention toward the most essential threats and opportunities and let the groundwork give risk response (Deloitte et al., 2012). Reliability is a useful method used to identify and quantify equipment and system failures that will prevent the achievement of its objectives. It consists of several tools such as fault tree analysis and lifetime data analysis by using Weibull distribution (International Energy Agency Solar Heating and Cooling Programme, 2015). However, it is difficult to estimate the reliability parameters of the systems up to a desired degree of accuracy by utilizing available information and uncertain data (Komal et al., 2010). Fig. 1 shows the process flow diagram for the simulation design system of solar water heater to be studied.

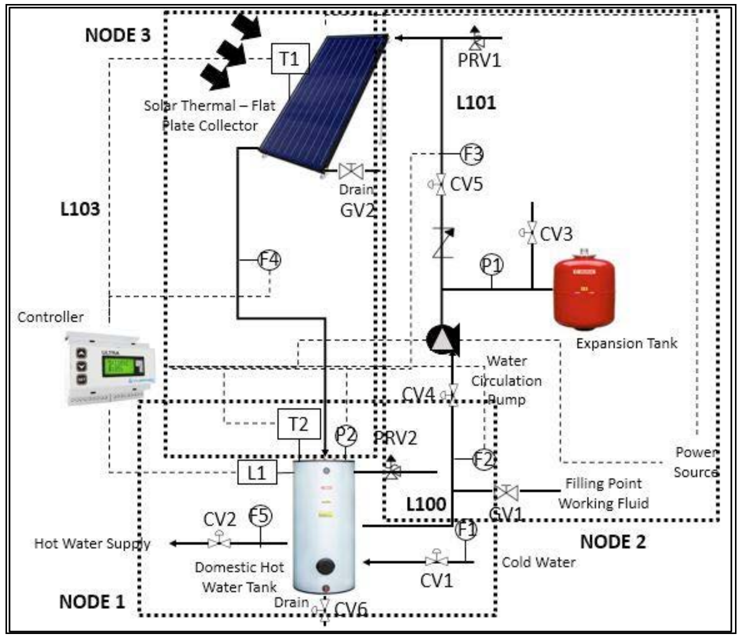

Figure 1 Schematic Diagram for Closed Loop Solar Water Heater System at Residential Area

This system is independent from the electrical water heater to provide the heating requirement during night time as it is supported with big storage tank. The cold water is fed into the storage tank with control valve (CV1) and flow sensor (F1) functioning to monitor the flow rate of cold water into the storage tank. The working fluid function as a heat transfer fluid and it is a mixing between water and glycol in a liquid phase only based on the ASHRAE Standard (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1991). This heat transfer fluid flows through the heat exchanger coil inside the storage water tank in closed loop pipeline system to transfer the thermal heat into the cold water inside the tank and then continuously flow through the solar collector drive by the circulating pump to absorb the energy from sun during bright day. The flow rate of working fluid is controlled by flow sensor (F2) and control valve (CV4) as it passes through pump and managed by control valve (CV5) and flow sensor (F3) after the pump system as it flows into the solar collector.

The gate valve (GV1) is used as an entry point to inject the working fluid if the volume is insufficient in the pipeline. It will ensure the volume of fluid is adequate to help in run the system by transferring the thermal energy. During the day time, the flat plate solar collector, which is mounted on top of the house roof, is exposed to sunlight and it will absorb the energy on the surface of essentially planar according to the working principle in ASHRAE standard. It will get hot, thus transferring the sun energy to the working fluid in a heat form (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 1991). The working fluid temperature is monitored by using temperature sensor (T1) which is installed on the solar collector while the flow rate is controlled by the flow sensor (F4) at line L103. The cold working fluid will be pumped back to the solar collectors for reheating process and non – return valve (NRV) is installed to ensure the fluid will only flow in one direction. The hot water is stored inside the same storage tank and its temperature is measured by temperature sensor (T2).

When there is a demand for hot water from users, it control valve (CV2) and flow sensor (F5) will ensure the flow rate demand is met. The level sensor (L1) and pressure sensor (P2) will the water level and pressure inside the storage tank will not exceed the allowable limit. If there is a sign of overflow in the storage tank, it will be detected by control valve (CV6) and if the pressure exceeds the set value, the pressure relief valve (PRV2) will respond accordingly. A controller system will manage the overall system and ensure that the fluid will circulate to the collector when there is sufficient heat available and supply the hot water to the producer at the stipulated temperature. For the piping system, the pressure will be monitored by the pressure sensor (P1) and when the pressure is too high, the pressure relief valve (PRV1) will act to reduce the high pressure build up.

2.0 METHOD

Hazard and Operability Study (HAZOP) method is used to identify process hazards and potential operating problems by using a series of guide words to study process deviations. Reliability analysis involves fault tree analysis and lifetime data analysis by using Weibull distribution for reliability part. Each of the main components involved are identified including solar collector, pump station (circulating pump) and solar controller, expansion tank and storage tank with heat exchanger. There are 3 nodes for HAZOP analysis as shown in Fig. 1. The data of the failure rate will be collected from available resource and reference. Fig. 2 shows the steps in constructing the HAZOP study and Fig. 3 shows the overall step to construct the reliability study. Weibull distribution is a mathematical method applied to estimate the life characteristic of the components in the system in terms of failure rates and reliability.

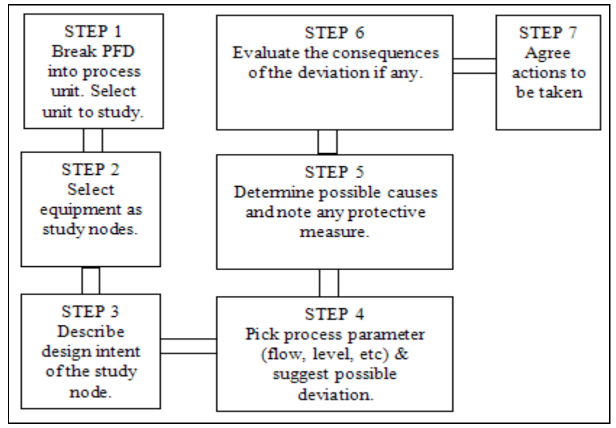

Figure 2 Steps in Constructing HAZOP Analysis

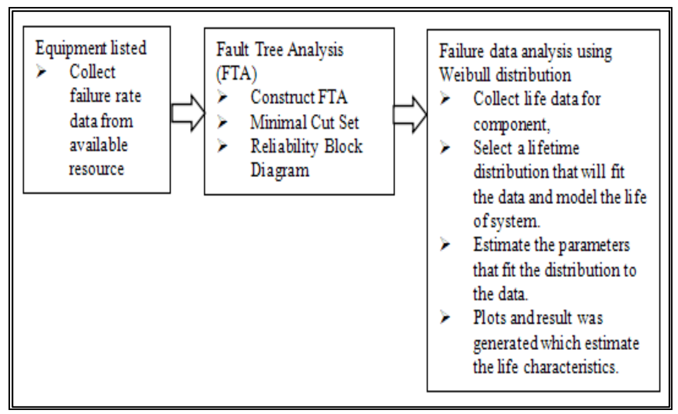

Figure 3 Step in Constructing Reliability Assessment

Table 1 Probability and Frequency of Each Gate and Formula Used in Weibull Distribution

Parameter	Input pairing	Formula	Equation
OR gate	P_A OR P_B	P (A OR B) = 1 – (1-P_A)(1-P_B)	(1)
AND gate	P_A AND P_B	P (A AND B) = P_AP_B	(2)
Probability density function (pdf)		$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$	(3)
Cumulative distribution function (cdf)		$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$	(4)
Reliability (Survival function)		$R(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}}$	(5)

3.0 RESULTS

3.1 Hazard and Operability Study (HAZOP) Analysis

For HAZOP analysis, findings were recorded and presented in Table 2, Table 3 and Table 4. Table 2 shows Node 1, which focuses on the inlet of cold water supply via CV1 and F1 to domestic hot water tank (DHWT) and the hot water supply outlet.

Table 2 Identification of Causes and Recommendations for Node 1

Item	Deviations	Possible Causes	Recommendation
Domestic Hot Water Tank (DWHT)	More Flow	Flow indicator (F1) and level indicator (L1) malfunction	1) Install Level Alarm High (LAH) at DHWT
		Control Valve (CV1 & CV2) malfunction due to incorrect input signal	2) Safety Operating Procedure
	Less Flow	Control Valve (CV1) partially open	1) Safety Operating Procedure
		Leakage at cold water supply	2) Periodic Maintenance
	No Flow	Control valve inadvertently closed / flow indicator fail open	Safety Operating Procedure
		Blockage cold water line	
	High Pressure	Pressure relief valve (PRV2) inadvertently closed	
	Low Pressure	Drop performance of DHWT	
	High Temperature	Temperature indicator (T2) malfunction	Install Temperature Alarm High (TAH)
	High Level	Flow indicator and level indicator (L1) malfunction	Install Level Alarm High (LAH) at DHWT
	Low Level	Control valve partially closed	Install Level Alarm Low (LAL) at DHWT
		Flow indicator partially open (wrong set point) / Control valve inadvertently partially closed	
	Other than Concentration	Presence of debris accumulation	Install Filter/Strainer before entering DHWT

Table 3 refers to Node 2 which covers from the working fluid flow to collector via water circulating pump. In this node, it was divided into two items which are feed line L100 and line L101 to flat plate collector and circulating pump.

Table 3 Identification of Causes and Recommendations for Node 2

Item	Deviations	Possible Causes	Recommendation
Feed Line to Flat Plate Collector	Less Flow	Leakage/ Insufficient cooling water supply	1)Safety Operating Procedure
			2)Periodic Maintenance
	No Flow	Blockage cold water line	1) Safety Operating Procedure
		Control valve fails to close or blocks	2) Install temperature indicator and controller to control tracing
			3) Regular inspection and maintenance of control valves
	Reverse Flow	Pump fail	
	High Pressure	Pump over speed/ overpressure	Install Pressure Indicator and Pressure Alarm High (PAH)
	Low Pressure	Pump poor performance	Install Pressure Alarm Low (PAL) and periodic maintenance
	High Temperature	Cold water system fails	Install Temperature Indicator and Temperature Alarm High (TAH)
	Other than Concentration	Presence of debris accumulation	
Circulating Pump	More Flow	Flow indicator (F3) fails, opening control valve (CV5)	
		Control valve fails open	
	Less Flow	DHWT storage empty	Install Level Alarm at DHWT
		Line 100 plugs	Use manual valve system
		Line 101 plugs	
	Fig. 1	Check valve (NRV) fails closed	
	No Flow	No level inside stock tank	
	Irregular Flow	Fluctuated pump performance	Restricted Orifice (RO)
	High Pressure	Control valve (CV5) fails closed	Use manual valve system
		Check valve (NRV) fails closed	Use manual valve system
		Line 101 plugs	
		Flow indicator (F3) fails, closing control valve (CV5)	
	Low Pressure	Control valve (CV5) fails open	Use manual valve system
		Line 100 plugs	Periodic maintenance
		DHWT storage empty	Install Level Alarm at DHWT
		Flow indicator (F3) fails, opening control valve (CV5)	Use manual valve system
	High Temperature	Control valve (CV5) fails closed	
		Check valve (NRV) fails closed	
		Line 101 plugs	
		Flow indicator (F3) fails, closing (CV5)	

For the last node refer to Table 4, it is focusing on hot working fluid line from flat plate collector, flow to domestic hot water tank (DHWT). Only one item recorded which is in line L103 to domestic hot water tank (DHWT).

Table 4 Identification of Causes and Recommendations for Node 3

Item	Deviations	Possible Causes	Recommendation
Line L103 to Domestic Hot Water Tank (DHWT)	More Flow	Flow Indicator (F4) malfunction due to incorrect input signal	
	Less Flow	Flow Indicator (F4) malfunction due to incorrect input signal	Install flow control valve
	No Flow	Flow Indicator (F4) malfunction - Fail open	Safety operating procedure
	High Pressure	High pressure hot water supply	Troubleshoot flat plate collector
	Low Pressure	Low pressure hot water supply	Troubleshoot temperature indicator
		Leakage at hot water L103 supply	
	High Temperature	High temperature hot water supply	
	Low Temperature	Temperature Indicator (T2) malfunction due to incorrect input signal	Install temperature control valve

3.2 Reliability Assessment

The data on the failure rate was collected from several sources and each symbol is listed in Table 5 below. Failure rate is required in order to calculate the reliability of each parameter. The reliability of each parameter has been calculated by using the formula indicated in this table and with the purpose of finding the value of failure probability.

Table 5 Failure Rate Data from Several Sources

Parameter	Symbol	Failure rate, λ (per year)	Refs	Reliability $R = e^{-\lambda t}$	Failure probability, P = 1-R
Leak Tank	B1	0.150672	IAEA [8]	8.6013E-01	1.3987E-01
Control Valve Fail	B2	0.15	FCEE UTM [8]	8.6071E-01	1.3929E-01
Pipe Corrode	B3	0.0001	UK HSE [10]	9.9990E-01	9.9995E-05
Pump Fail to Run	B4	0.297840	US DOE [11]	7.4242E-01	2.5758E-01
Pressure Relief Valve Fail	B5	0.002	FCEE UTM [9]	9.9800E-01	1.9980E-03
Pump Fail to Stop	B6	0.12264	US DOE [11]	8.8458E-01	1.1542E-01
Temperature Sensor Fail	B7	0.027	FCEE UTM [9]	9.7336E-01	2.6639E-02
Controller Fail	B8	0.149796	IAEA [8]	8.6088E-01	1.3912E-01
Collector Fail	B9	0.099864	US DOE [11]	9.0496E-01	9.5040E-02
Pump Breakdown	B10	0.021462	OREDA [12]	9.7877E-01	2.1233E-02
Power Tripped	B11	0.0122640	US DOE [11]	9.8781E-01	1.2189E-02
Expansion Tank Fail	B12	0.134028	IAEA [8]	8.7457E-01	1.2543E-01
Gasket Fail	B13	0.000005	UK HSE [10]	1.0000E+00	5.0000E-06
Pump Leakage(Internal)	B14	0.0069204	OREDA [12]	9.9310E-01	6.8965E-03
Casing Fail	B15	0.00003	UK HSE [10]	9.9997E-01	3.0000E-05
Pump Seal Fail	B16	0.007008	FCEE UTM [9]	9.9302E-01	6.9835E-03
HEX in Storage Tank Fail	B17	0.28908	IAEA [8]	7.4895E-01	2.5105E-01

The fault tree diagram is generated based on the failure parameter in Table 5 (Fig. 4). The advantage of this approach is the inclusion of their impacts on each other. Table 6 shows the results of probability, P for each gate in the FTA.

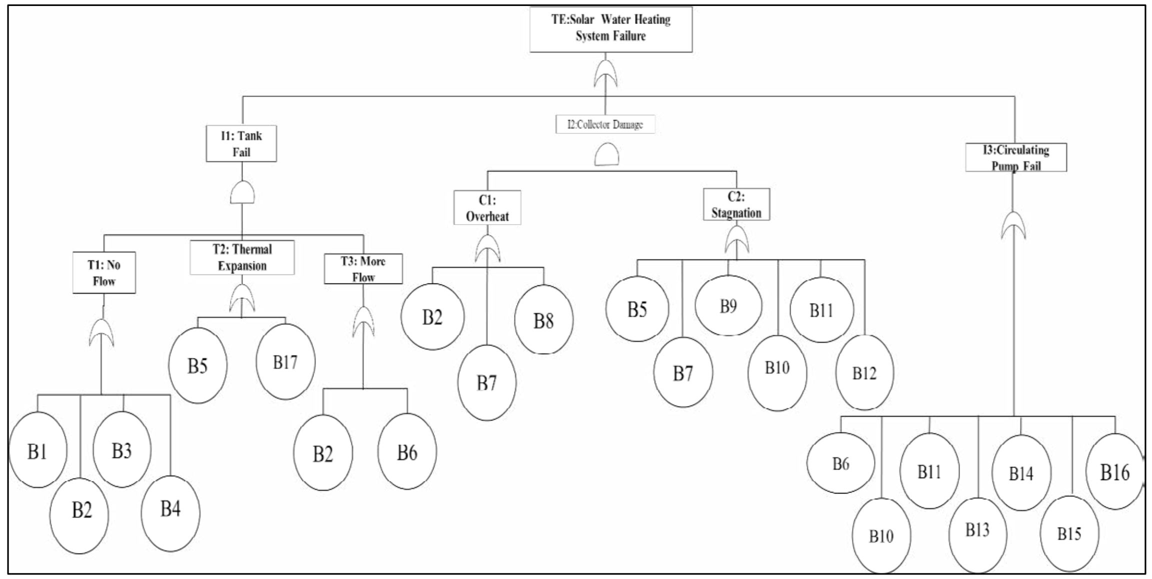

Figure 4 Fault Tree Analysis of Solar Water Heating System

Table 6 Probability of Each Gate

Input pairing	Probability, P
P_{T1} (B1 OR B2 OR B3 OR B4)	4.5043E-01
P_{T2} (B8 OR B17)	2.5254E-01
P_{T3} (B2 OR B6)	2.3863E-01
P_{C1} (B7 OR B2 OR B8)	2.7145E-02
P_{C2} (B7 OR B9 OR B10 OR B11 OR B12 OR B5)	2.7877E-01
P_{I1} (P_{T1} AND P_{T2} AND P_{T3})	2.5667E-01
P_{I2} (P_{C1} AND P_{C2})	7.1552E-02
P_{I3} (B10 OR B11 OR B13 OR B14 OR B15 OR B16 OR B6)	1.5661E-01
P_{SYSTEM} (P_{I1} OR P_{I2} OR P_{I3})	2.3822E-01

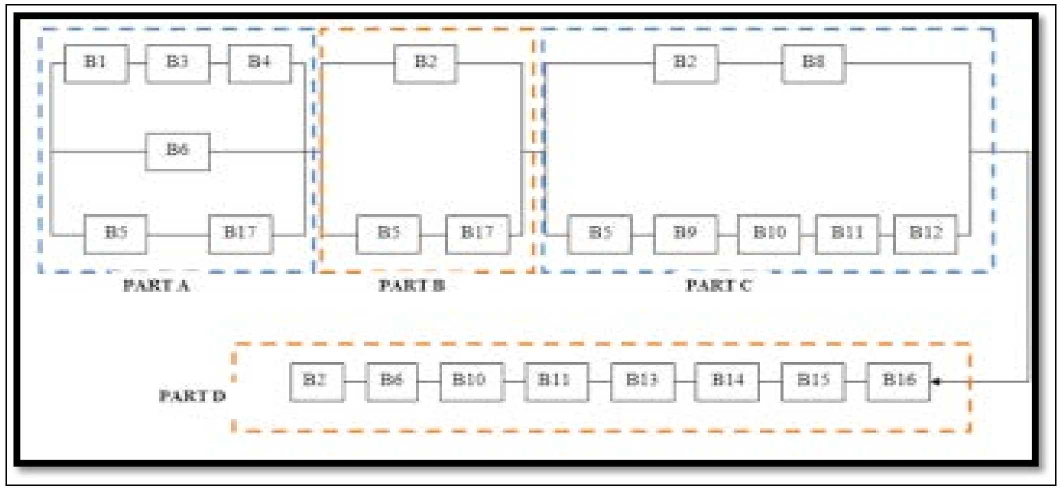

Figure 5 Reliability Block Diagram of Solar Water Heater System

From the minimal cut set by using mathematical form of Boolean algebra, system reliability and analysis can be transformed into the block diagram to illustrate the network relationships as shown in Fig. 5. For Fig. 6, 7 and 8, they show the graph by using Weibull distribution (two parameters) of which α indicates scale and β is shape parameter. From the FTA diagram, storage tank, solar thermal collector and circulating pump are defined as intermediate events. Therefore, the scale and shape for each of the solar water heater system components will be derived from probability plotting serial of data that will be computed in the excel tool. The shape value for storage tank, collector and pump are 3, 2.5 and 2.09 respectively while for scale value they are 7.5, 6.5 and 6.6 respectively. All graphs in Fig. 6, 7 and 8 plotted based on failure data collected and by using equation (3), (4) and (5) respectively. From equation (4), the cumulative distribution function data is plotted in graph.

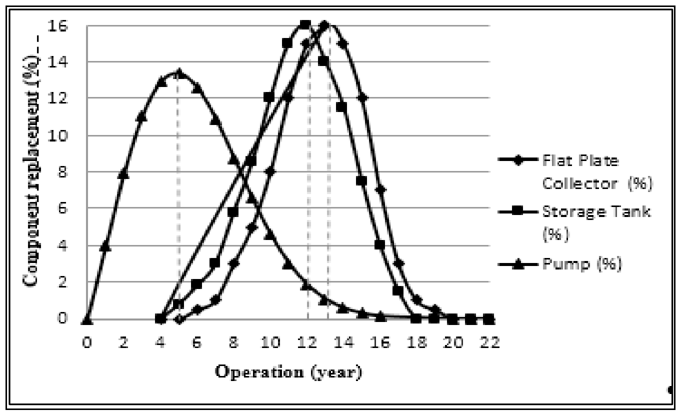

Figure 6 Component Replacement in SWH System

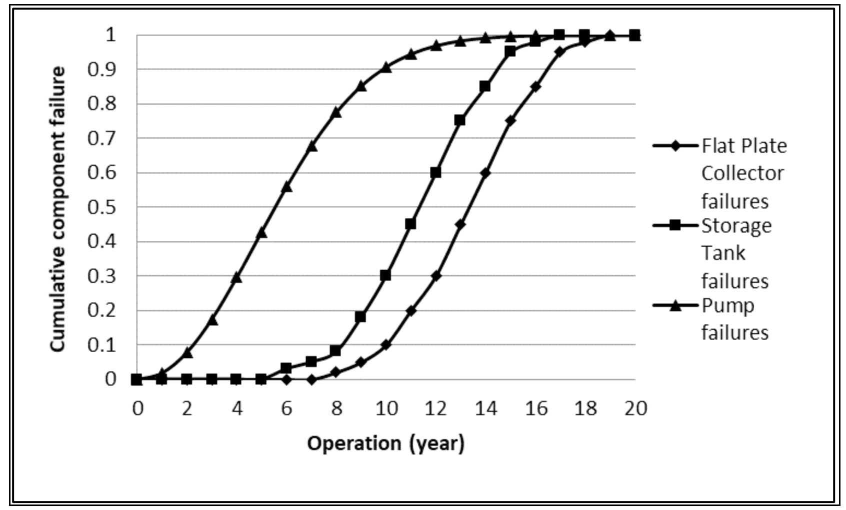

Figure 7 Cumulative distribution function

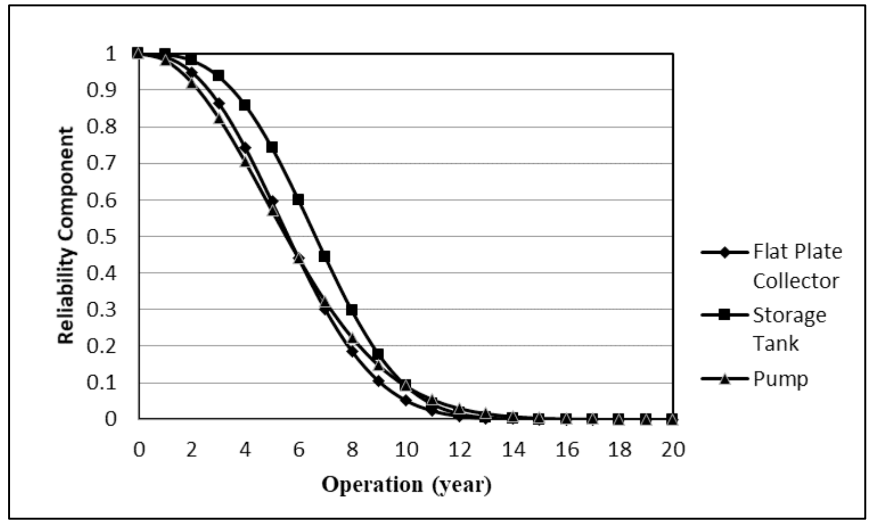

Figure 8 Reliability (Survival Function) of SWH System

4.0 DISCUSSION

The suitable parameter chooses that related to node 1 consists of flow, pressure, temperature, level and concentration with suitable deviation based on Table 2. There are five actions that need to be taken to address the HAZOP parameter of flow which may have three different deviations (more, less and no). While for the level parameter in, two actions need to be taken which are installing level alarm high and level alarm low at DHWT. Only one action required (install temperature alarm high at DHWT) for the temperature parameter. For Table 3, the parameters involved including flow, pressure, temperature and concentration for first item. While for the second item, only flow, pressure and temperature were involved. For first item, there are five actions highlighted to be taken for flow parameter, two actions (install pressure indicator and pressure alarm high and install pressure alarm low and periodic maintenance) suggested for pressure and only one action recommend (install temperature indicator and temperature alarm high) for temperature. For the second item, parameter flow has three actions being suggested, while there are six actions need to be taken for pressure where some actions are repeated for different causes. In Table 4, flow, pressure and temperature were involved as parameters. There are two actions recommended for flow and pressure parameters respectively while only one action (install temperature control valve) suggested for temperature parameter.

The step to construct FTA as shown in Fig. 4 is based on top event connected to intermediate event, sub intermediate event and basic event. Firstly, the storage tank requires three sub intermediate events to occur (no flow, thermal expansion and more flow) in order for the storage tank to fail. Secondly, overheating and stagnation of intermediate events must occur to contribute to collector damage. Lastly, the circulating pump will fail when any of the 7 of basic events occurs. The storage tank can fail if no cold-water was supplied into the tank and no heat transfer from the working fluid. The thermal expansion can occur and cause explosion if the tank temperature is high. If more water flows into the tank, it will overflow and contribute to tank fail. If the temperature is too high, overheating can occur and could cause collector damage. Stagnation occurs if flow of working fluid is interrupted, causing the solar collector to absorb more heat that cause damage to collector. Therefore, 24 basic events identified for three intermediate events including collector, tank and pump and which there are seven similar basic events repeat such as control valve fail (B2), pressure relief valve fail (B5), pump fail to stop (B6), temperature sensor fail (B7), pump breakdown (B10) and power tripped (B11) for different intermediate event.

The overall probability for solar water heating system is 0.23822 by referring to Table 6. It indicates that the probability of the system to fail is very low by using equation (1) and (2) in Table 1. The computational process is based on Boolean algebra mathematical rule for minimal cut set. From Fig.5, the solar water heater system is a combination of series and parallel configuration. The RBD has been divided to four parts for better explanation. It begins with part A with series configuration of three basic events which are B1, B3 and B4 that are connected parallel to B6 and parallel to the series arrangement of B17 and B5. For part B, the basic event B2 is parallel to the series configuration of B5 and B17. Part C shows the series configuration of B2 and B8 basic event is connected parallel to series arrangement of B5, B9, B10, B11 and B12. Finally, for part D, it only has the combination of 8 basic events that in series configuration which are B2, B6, B10, B11, B13, B14, B15 and B16. The connection for part A, B C and D are series configuration. Subsequently, in series configuration, if any basic event fails to operate, it will result in the failure of the entire system. For example, if any of the eight basic events of part D fails, the solar water heater system will not function. In other words, all of eight basic events must succeed and operate in good condition to ensure that the solar water heater system could succeed in producing the hot water. Parallel arrangement is also called as redundant unit. At least, one of the units (basic event) must function for the system to operate. As presented in part B, at least B2 or unit (B5 and B17) must be functioning for the solar water heater system to operate.

Fig. 6 shows the probability of component replacement due to failure, in which the pump has the highest failure in the first year compared to other components. From the graph, the mode value (the highest failure rate) for the flat plate collector, storage tank and pump are 13 years, 12 years and 5 years respectively. The highest failure rate of collector and storage tank was 16% while pump failure rate is around 13.37 %. The failure frequency of pump is the highest compared to other components. The figure shows that the pump requires maintenance 5 years of operation. The number of failure decreases after 5 years since the sequence maintenance and replacement certain parts of pump. While for collector the graph declines after 13 years of operation because reduction in number of remaining collector still intact. Fig. 7 illustrates cumulative distribution function of component in solar water heater (SWH) system. According to the graph 10% of collector will face some sort of part component failures within 10 years, which is less compared to storage tank (30%) and pump (90%). In 10 years, the pump requires regular replacement of parts and service.

Fig. 8 shows the reliability of three components in solar water heater system where the probability of each component will be operating over some period of time. The survival of all three components reduces the times rises. The reliability plotted only models the time until the failure occurs without concern for the time to repair. The estimation of reliability of each component in one year for storage tank, flat plate solar thermal collector and circulating pump are 0.9976, 0.9907and 0.9808 respectively. It indicates that the pump has the highest frequency for its components to fail completely compare to other two SWH components due to expected wear and tear. Other factors include the circulating pump is operating at high temperature above the operating temperature as the solar collector is absorbing more heat from the sun during hot days due to the fluctuation of the climate condition. The reliability graph for flat plate collector component become zero after 12 years of operation. After 13 years, the survival of storage tank and circulating pump become zero and for is after 12 years. Therefore, the storage tank and circulating pump have better life time even though slightly different in terms of reliability.

5.0 CONCLUSION

The HAZOP analysis has identified several causes for each of the three nodes of the solar thermal heating system which can potentially lead towards the system failure. There are few actions being highlighted to address all 49 potential hazards and to enhance the safety level of the system for the safety users. The FTA has determined 24 basic events for three intermediate events including collector, tank and pump and there are 7 similar basic events repeat such as B2, B5, B6, B7, B10 and B11. The calculated failure probability of the system is 0.23822. Weibull probability distribution identified the probability density function for three components and it is found all the components increase exponentially against time. The estimation reliability of each component in 1 year for storage tank is 0.9976, collector (flat plate) is 0.9907 and circulating pump is 0.9808. The computed reliability for the overall system is 0.9693 which indicates that this independent closed loop solar water heater system is long lasting.

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