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Original Article

The detection and diagnosis model for small scale MSLB accident

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ABSTRACT

The main steam line break accident is an essential initiating event of the pressurized water reactor. In present work, the fuzzy set theory and the signal-based fault detection method has been used to detect the occurrence and diagnosis of the location and break area for the small scale MSLB. The models are validated by the AP1000 accident simulator based on MAAP5. From the test results it can be seen that the proposed approach has a rapid and proper response on accident detection and location diagnosis. The method proposed to evaluate the break area shows good performances for small scale MSLB with the relative deviation within ±3%.

1. Introduction

After the Three Mile Island accident and the Chernobyl accident, safety problems at nuclear power plant (NPP) have emerged as a global concern and the Fukushima-Daiichi accident shook the world again in 2011. Numerous of accident management support systems (AMSS) have been developed and installed in a number of NPPs, as MARS [1], ERSS [2], ADAM [3,4], CAMS [5,6], SAMEX [7], the smart support system for diagnosing severe accidents in nuclear power plants [8] in the fast running mode to support the accident management. Identification of the initiating even is the first challenge for AMSS, and at present, there is no unified and effective strategy to solve this problem.

The main steam line break (MSLB) is an essential initiating event of the pressurized water reactor (PWR). From the history of the operation, the probability of 100% scale MSLB accident is very low. However, the leaks and cracks in the main steam line cannot be avoided with the ageing of the NPP and the degradation of material properties [9]. For MSLB accident, the existing researches mainly focus on the characteristics and uncertainty analysis [10], including the responses of containment [11]. Although, the data-driven routes to fault detection and diagnosis (FDD) in industrial systems have been tackled by Chiang et al. [12] and Hines et al. [13]; there is still a lack of research on the on-line diagnosis model for MSLB accident, especially on the method for break area assessment.

In order to improve the efficiency of the AMSS and implement the on-line simulation of the accident, more exploration and research is needed to identify the information of the initiating event, such as the accident type, the location and the beak area. In this paper, based on the experiences of accident analysis and the monitoring parameters in NPP, a signal-based FDD method combined with the fuzzy set theory [14–16]) has been used to diagnosis the occurrence and location of MSLB accident. Meanwhile, a method to evaluate the break area of the small scale MSLB accident has been proposed. It is expected that the method can improve the abilities of the AMSS and provide more detailed information to support the accident management.

2. Diagnosis model of MSLB accident

2.1. Accident symptoms

The nuclear power plant is a large-scale complex system. The system is highly nonlinear, and under the coupling action of various physical effects and the uncertainty of human factors, the power plant may be in a “chaotic” state in the case of an accident. According to the position of the rupture, the initial reactor conditions and the accompanying malfunctions assumed, a variety of accidents with different consequences arise. For the inside

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Nomenclature

ADAM	Accident diagnostic, analysis and management system
AP1000	Advanced passive light water reactor
AMSS	Accident management support systems
CAMS	Computerized accident management support system
DCS	Distributed control system
ERSS	Emergency response support system
FDD	Fault detection and diagnosis
MARS	MAAP accident response system
MAAP5	Modular accident analysis program, version 5
MCR	Main control room
MSLB	Main steam line break
NPP	Nuclear power plant
PWR	Pressurized water reactor
PZR	Pressurizer
SEMEX	Severe accident management expert system
SG	Steam generator

Superscripts

+	Increasing state
−	Decreasing state

Subscripts

as	Accident symptom
b	Break
cr	Critical
d	Discharge
D_L	Low limit of decreasing state
H	High
I_H	High limit of increasing state
L	Low
Lo	Location of the accident
N_L	Low limit of normal state
N_H	High limit of normal state
Occ	Occurrence of the accident
Ref	Reference
s	Steam

containment MSLB accident, within a period of the accident, the rapid flashing in the SGs and the steam discharge to the containment will cause (see Fig. 1):

- The reactor power, containment pressure, containment temperature, containment humidity, containment sump water level, condensed water in the ventilation system, SG steam flow rate and main feed water flow rate increase.
- The steam generator (SG) pressures, SG water levels, cold leg temperatures, average core temperature, pressurizer (PZR) pressure, PZR water level, main condenser water level and main feed water temperature decrease.
- There is no significant change for the containment radioactive.

The MSLB accident at 1# SG has been carried out with the break areas of 2.5% main steam line flow area (0.5895 m^2) based on the MAAP5 model of AP1000 [17]. The transient has been run for 1500 s and the MSLB accident is inserted at 1000 s. Before the accident, the plant is at full power and the safety functions are under the state of automatic control after the accident. The characteristics of symptoms according to the accident progression are depicted in Fig. 2.

In case of an accident, there will be various warnings and safety signals. According to the characteristics of the accident symptoms, the sphere of influence, and the response sensitivity of the accident parameters, the symptoms can be divided into three hierarchies, as:

- First hierarchy: The reactor power, average core temperature, containment pressure, SG pressures, SG steam flow rate.
- Second hierarchy: PZR pressure, PZR water level, cold leg temperatures, containment temperature, containment humidity, SG water levels, main feed water flow rate.
- Third hierarchy: containment sump water level, condensed water in the ventilation system, main feed water temperature, main condenser water level.

In this paper, thinking about the response speed to identify the occurrence and location of the MSLB accident, symptoms in the first hierarchy will be used to build the diagnosis model.

2.2. Diagnosis logic

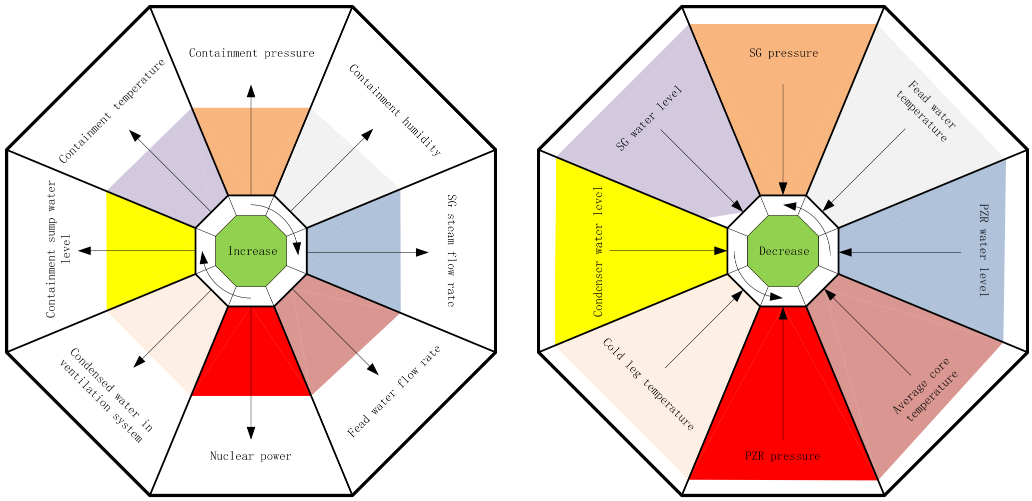
For accident diagnosis, the symptoms are needed to transfer into the system. The structure of the accident diagnosis logic used in this paper is shown in Fig. 3. The relationships between the results and the accident states of the NPP are expressed by a set of if-then rules. The inputs are the signals provided by the distributed control system (DCS). The first step is the sampling of the symptoms, and the next is the implement of the linguistic rules which deal with the relationships between the membership values and the symptom behaviors. Finally, the accident occurrence and location will be solved based on the processing of these memberships.

Take the body temperature of human beings as an example, 36.5–37.2 °C is normal, 37.2–38 °C is low fever and the body temperature beyond 38 °C is high fever. Any accident symptom also has three states as normal, increasing and decreasing (see Fig. 4).

If the value of the symptom is within the boundaries of a normal state, the memberships of increasing and decreasing are 0. When the value is between high boundary of normal state and symptom's high limit, the increasing membership is a linear equation according to the current value of the symptom. Or if it is between the low boundary of the normal state and the symptom's low limit, the decreasing membership is a linear equation too. When the value of the symptom is higher than the high limit, the increasing membership is 1, and if it is lower than the low limit, the decreasing membership is 1.

For each accident symptom, the states of normal, decreasing and increasing will be parameterized through Eqs. (1) and (2) according to the current value and the limits in Table 1. The limits are based on the comprehensive consideration of the instrument response precision and the sensitivity of the accident feature recognition.

$$\mu_{as}^{+}(t)=\begin{cases}0, \mathrm{Sym}_{N_L}\le \mathrm{Sym}(t)\le \mathrm{Sym}_{N_H}\\ \dfrac{\mathrm{Sym}(t)-\mathrm{Sym}_{N_H}}{\mathrm{Symptom}_{I_H}-\mathrm{Symptom}_{N_H}}, \mathrm{Sym}_{N_H}<\mathrm{Sym}(t)\le \mathrm{Sym}_{I_H}\\ 1, \mathrm{Sym}_{I_H}<\mathrm{Sym}(t)\end{cases} \tag{1}$$



(a) Increasing symptoms (b) Decreasing symptoms

Fig. 1. Accident symptoms of MSLB accident.

$$\mu_{as}^{-}(t)=\begin{cases}0, \mathrm{Sym}_{N_L}\le \mathrm{Sym}(t)\le \mathrm{Sym}_{N_H}\\ \dfrac{\mathrm{Sym}_{N_L}-\mathrm{Sym}(t)}{\mathrm{Sym}_{N_L}-\mathrm{Sym}_{L}}, \mathrm{Sym}_{D_L}\le \mathrm{Sym}(t)<\mathrm{Sym}_{N_L}\\ 1, \mathrm{Sym}(t)<\mathrm{Sym}_{D_L}\end{cases} \tag{2}$$

Where, $\mu_{as}^{+}(t)$ is the membership of increasing state; $\mu_{as}^{-}(t)$ is the membership of decreasing state; $\mathrm{Sym}(t)$ is the current value of the accident symptom; Sym_{N_L} is the value of high limit for normal state; Sym_{N_H} is the value of low limit for normal state; Sym_{I_H} is the value of high limit of increasing state; Sym_{D_L} is the value of low limit for decreasing state.

To diagnose the occurrence of MSLB accident, the membership function of MSLB for every sampling point can be expressed by Eq. (3). When the output of Eq. (3) is larger than a reference value (such as 0.8, 0.9 or 0.95), the occurrence of MSLB will be confirmed.

$$\mu_{\mathrm{Occ}}(t)=\sum_{i=1}^{M} W(i)\cdot\mu_{s}^{+}(t)+\sum_{i=M+1}^{N} W(i)\cdot\mu_{\mu_s}^{-}(t) \tag{3}$$

Where, $\mu_{\mathrm{Occ}}(t)$ is the membership function of MSLB accident; $W(i)$ is the weight factor of each symptom.

The membership function of MSLB is a complex parameter which is based on the symptoms monitored by the operators in the main control room (MCR). The model to get the membership function of MSLB accident can be regarded as a digital representation of the operator's judgment.

3. Determination of the break location and area

3.1. Beak location

The diagram of main steam lines is shown in Fig. 5, which illustrates that the main steam header is connected to the SGs and steam turbine. During the normal operation, the isolation valves and the turbine stop valves are open and different valves control the flow rates in these steam lines.

In this paper, the determination of MSLB location is limited to provide macroscopic regional information of inside or outside the containment and at which SG. Based on the parameters of the containment pressure, the accident is inside or outside the containment can be distinguished through Eq. (1).

In case of a MSLB accident, there will be significant differences between the broken and unbroken SGs, just as the steam pressure and steam flow rate (see Fig 2 (d) and (e)). For each selected symptom and the reference value, the change curves can be drawn according to the sampling intervals (see Fig. 6). The covered area of each symptom can be calculated along the accident progression. The analysis model can be built as Eq. (4) to calculate the deviation degree from the reference state. In Eq. (4), the low limit is set as ±2.5% and the high limit is ±5.0%.

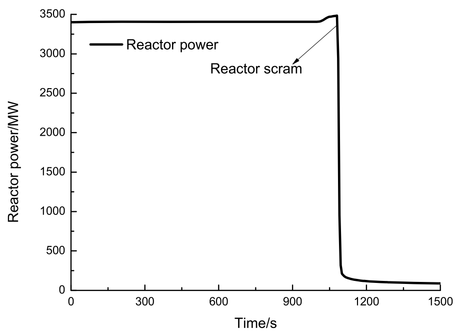
$$\mu_{Sym}(t)=\begin{cases}0, \dfrac{\mathrm{A_{Sym}}(t)-\mathrm{A_{Ref}}(t)}{\mathrm{A_{Ref}}(t)}\le Limit_L\\ f\left(\dfrac{\mathrm{A_{Sym}}(t)-\mathrm{A_{Ref}}(t)}{\mathrm{A_{Ref}}(t)}\right), Limit_L<\dfrac{\mathrm{A_{Sym}}(t)-\mathrm{A_{Ref}}(t)}{\mathrm{A_{Ref}}(t)}\le Limit_H\\ 1, \dfrac{\mathrm{A_{Sym}}(t)-\mathrm{A_{Ref}}(t)}{\mathrm{A_{Ref}}(t)}>Limit_H\end{cases} \tag{4}$$

Where, $\mu_{Sym}(t)$ is the likelihood of MSLB accident location for each symptom according to the accident progression; $\mathrm{A_{Sym}}(t)$ is the covered area of each selected symptom; $\mathrm{A_{Ref}}(t)$ is the covered area based on the reference value; $Limit_L$ is the low limit of the relative difference; $Limit_H$ is high limit of the relative difference.

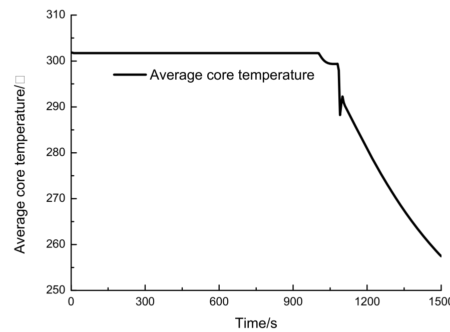
Through Eq. (5), the total likelihood of MSLB accident location for each SG can be calculated. Take the break at 1#SG main steam line as an example, if the value of Eq. (5) for 1#SG is larger than a reference point of 0.8, the MSLB accident is more likely located at 1#SG.

$$\mu_{Lo}(t)=\sum_{i=1}^{i=N}\mu_{Sym}(t) \tag{5}$$

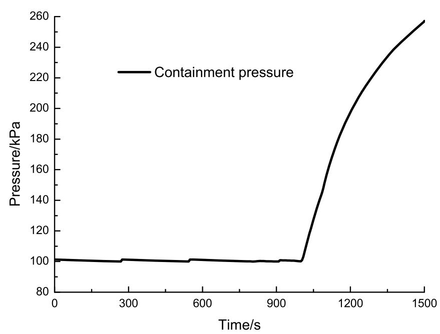
Where, $\mu_{Lo}(t)$ is the total likelihood of MSLB accident location for each SG.



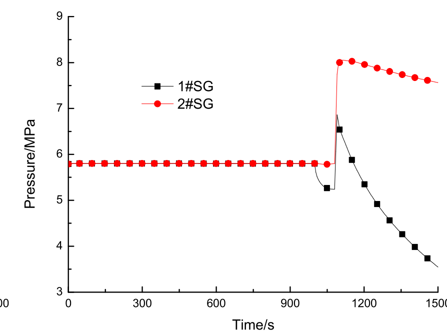
(a) Reactor power



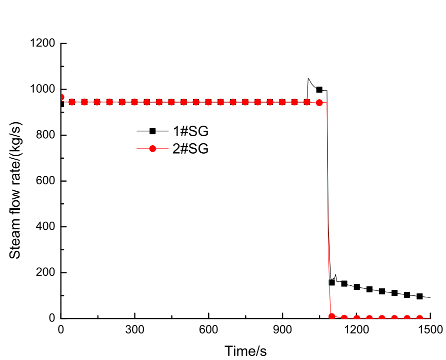
(b) Average core temperature



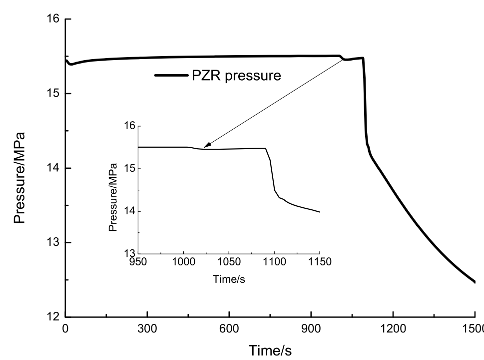
(c) Containment pressure



(d) SG pressure

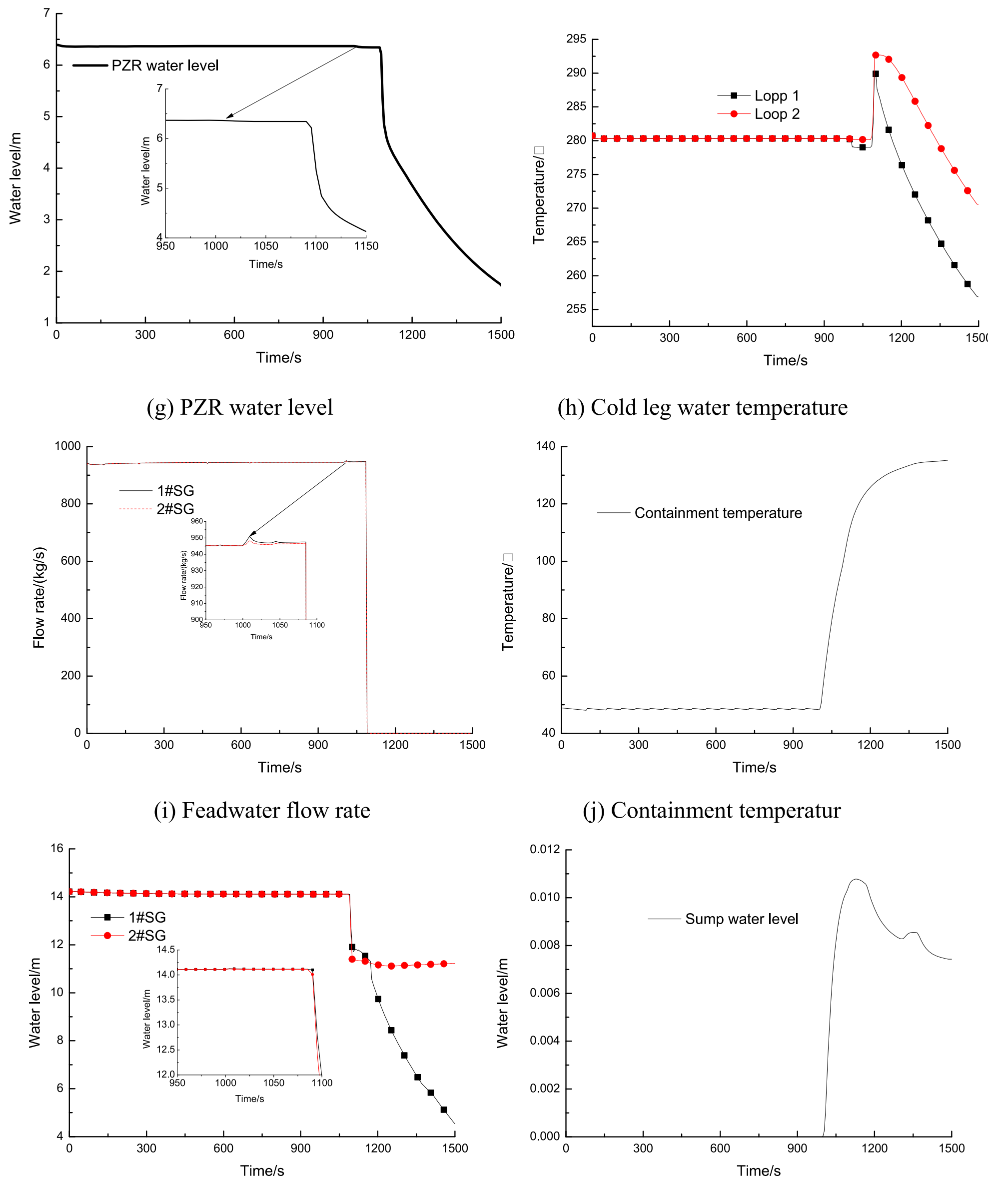


(e) SG steam flow rate



(f) PZR pressure

Fig. 2. Characteristics of the accident symptoms.



(g) PZR water level (h) Cold leg water temperature

(i) Feadwater flow rate (j) Containment temperatur

(k) SG water level (l) Containment sump water level

Fig. 2. (*continued*).

3.2. Beak area

No matter the break is inside or outside the containment, once the main isolation valve is triggered to be closed with the steam pressure lower than the set points of atmospheric release valve and the safety relief valve, the main steam flow rate is reflected as the steam release through the break. During the power load operation, the secondary side pressure of SG will be maintained at high level, and for a certain period of the accident, the steam discharge from the break will fulfill the constraints of steam critical flow. So, for the MSLB accident with a given discharge area, the steam flow rate can be expressed as below [18]:

$$W_{cf}(t) = 3.6\cdot K_d\cdot A\sqrt{\frac{P_s(t)}{\upsilon_s(t)}}\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{6}$$

Where: W_{cf} is the critical mass flow rate, kg/h; A is the discharge area, mm^2; K_d is the actual coefficient of discharge; $P_s(t)$ is the steam pressure, MPa; $\upsilon_s(t)$ is the specific volume at inlet condition; k is the isentropic coefficient at inlet condition.

The equivalent break area can be expressed as:

$$A_b(t) = \frac{W_{cf}(t)}{3.6\cdot K_d\cdot\sqrt{\frac{P_d(t)}{\upsilon_s(t)}}\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} = \frac{W_s(t)}{3.6\cdot K_d\cdot\sqrt{\frac{P_d(t)}{\upsilon_s(t)}}\sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}} \tag{7}$$

Where, $A_b(t)$ is the equivalent break area of MSLB for every sampling point, mm^2 and $W_s(t)$ is the steam mass flow rate for all the steam generators, kg/h.

4. Results and discussion

In order to check the models above, two MSLB accidents at 1# SG are carried out with the break areas of 2.5% and 5.0% main steam line flow area (0.5895 m^2). Before the accident, the plant is at full

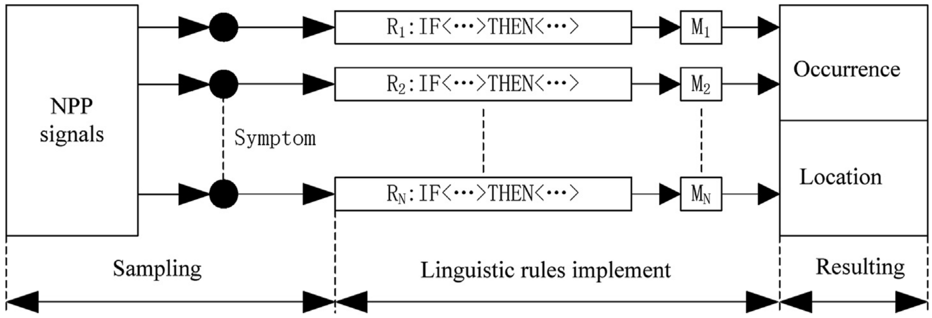


Fig. 3. Structure of the accident diagnosis logic.

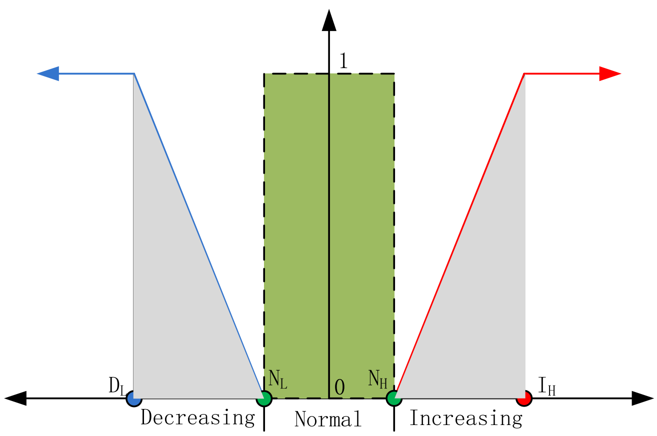


Fig. 4. Parameterized model for accident symptoms.

Table 1
Symptom limits in the model.

Symptom	Normal	Increasing	Decreasing
Core thermal power	±1.0%	+2%	−2%
Average core temperature	±0.5 °C	+1.5 °C	−1.5 °C
Containment pressure	±10 kPa	+20 kPa	−20KPa
SG pressure	±15 kPa	+30 kPa	−30kPa
SG steam flow rate	±1.0%	+5.0%	−5.0%

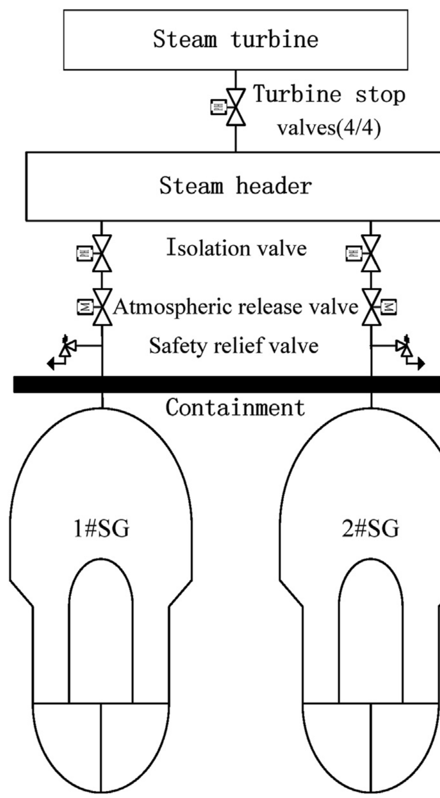


Fig. 5. Typical diagram of main steam lines with steam header.

power and the MSLB accident is injected into the accident simulator of AP1000 modeled by MAAP5. The safety functions are under the automatic control mode, and the symptoms between the occurrence of the accident and the reactor scram are used to validate the MSLB accident diagnosis model.

Fig. 7 shows the diagnosis results of the occurrence and location for 2.5% scale MSLB. At about 10 s after the accident, the abnormal state in 1#SG can be detected. At about 37 s after the accident, the energy release inside the containment and the occurrence of MSLB will be ensured. Before the reactor scram, the MSLB accident with a full information of “This is an inside containment MSLB located at 1#SG” can be provided.

The performances of the model for 5.0% scale MSLB accident is shown in Fig. 8. The steam discharge of 5.0% scale MSLB accident is larger than that of 2.5% scale MSLB. So, the abnormal state in 1#SG and inside containment energy release can be earlier detected. The full information of an inside containment MSLB accident at 1#SG main steam line can be provided at 23s, which is also before the time of reactor scram.

The results of break area evaluation are shown in Figs. 9 and 10 with $K_d = 0.985$ [19]. The time average break areas evaluated are $0.014554\ m^2$ and $0.029643\ m^2$ respectively for 2.5% and 5.0% scale MSLB accident. The relative deviation is within ±3%.

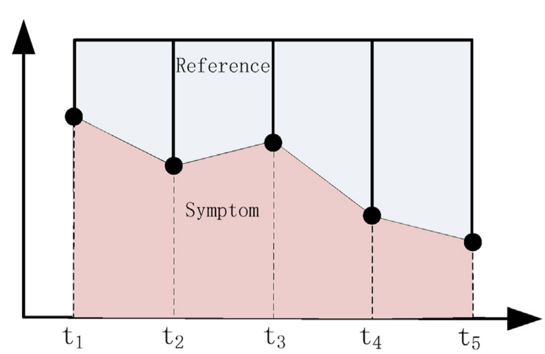


Fig. 6. Covered area of the signal.

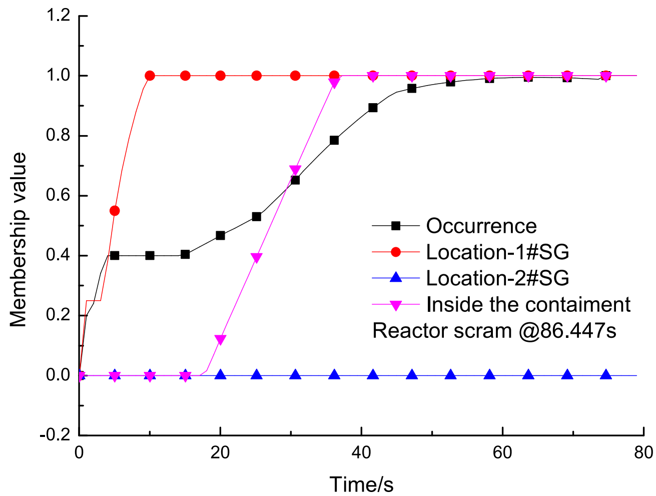


Fig. 7. Diagnosis results of the 2.5% scale MSLB.

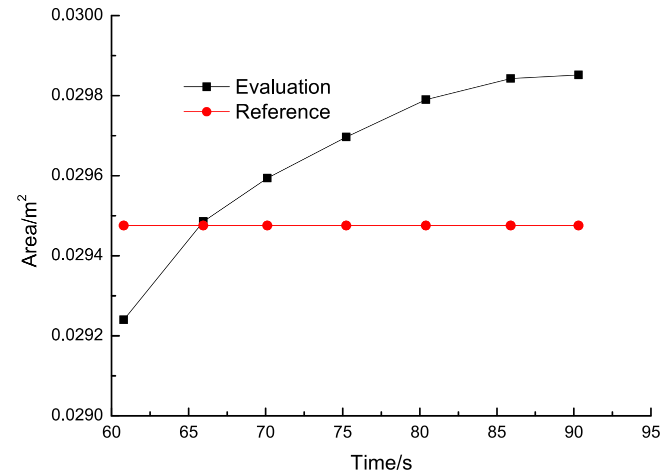


Fig. 10. Evaluation of break area for 5.0% scale MSLB.

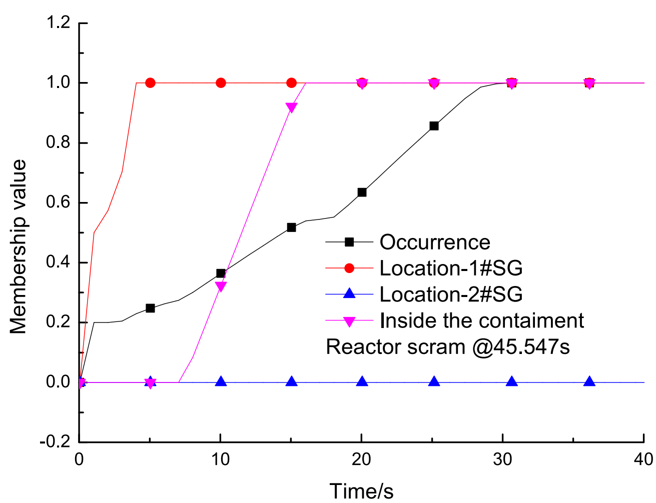


Fig. 8. Diagnosis results of the 5.0% scale MSLB.

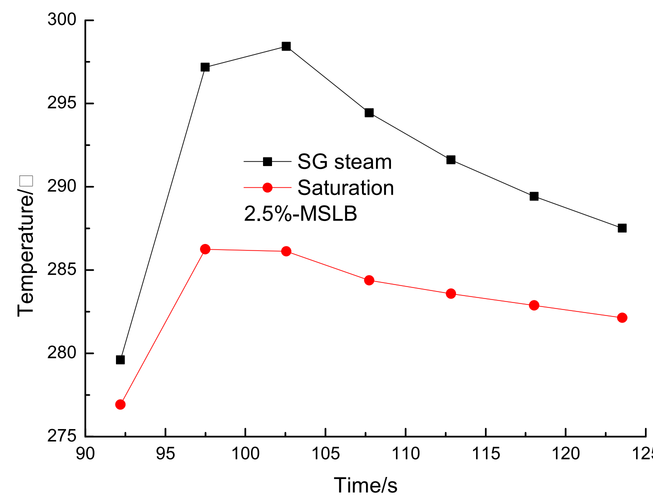


Fig. 11. Temperatures of the steam and saturation.

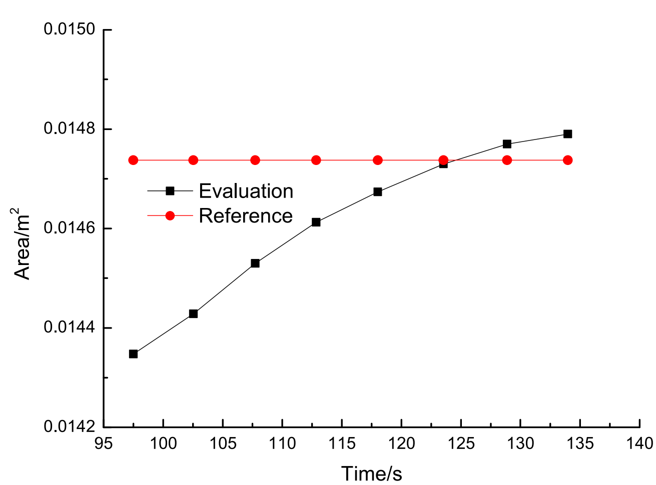


Fig. 9. Evaluation of break area for 2.5% scale MSLB.

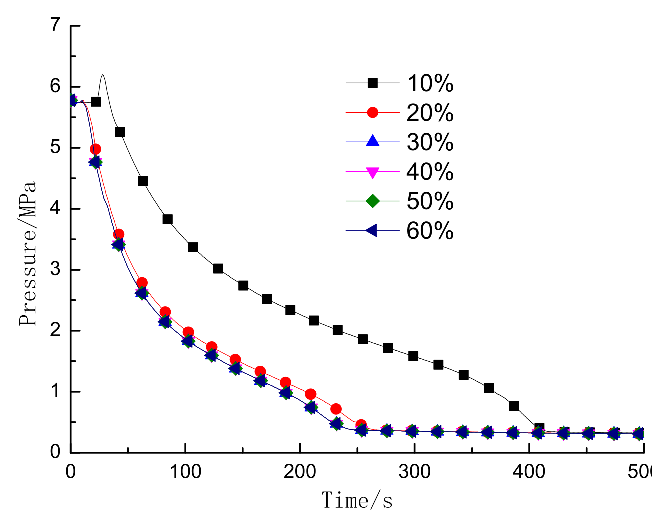


Fig. 12. Effects of the break scale on steam pressure of broken SG.

For the break area evaluation through Eq. (7), the state of steam in SG is assumed as saturated steam. However, in the transient of MSLB accident, the steam temperature in SG is slightly higher than saturation (see Fig. 11). For these reasons, the specific volume will be smaller than the actual resulting in the relative deviation of the break area with the reference values.

For large scale MSLB accident, just as the break area is larger than 20% of the main steam line flow area, the transient progression is so fast, that the SG pressure will quickly decrease near to the receiving environment. So, it is very difficult to use the steam mass flow to estimate the break area. On the other hand, the break area for large scale MSLB accident is so large that the accident progression will tend to be uniform (see Fig. 12). The probability of large scale MSLB accident is very low, so the small scale MLSB accident is the focus of the research, especially for the development of accident detection and diagnosis model.

5. Conclusions

The detection and diagnosis method of the small scale MSLB accident has been studied. A signal-based FDD method combined with the fuzzy set theory has been proposed to diagnosis the occurrence and location of the MSLB accident. From the test results, it can be seen that the proposed approach has a rapid and proper response on the small scale MSLB accident. According to the characteristics of the accident, a model-based method has been used to evaluate the break area of the small scale MSLB. During a certain period of the accident that fulfills the constraints of steam critical flow, the method has good performances and the relative deviation between the assessment and reference values is within ±3%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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