Fault diagnosis based on multilevel flow model for high temperature gas - cooled reactor

LI Dianbin, ZHOU Zhiwei, ZHOU Yangping[1], TANG Yang, SHI Lei, DONG Yuejie, and ZHANG Zuoyi

1. *Institute of Nuclear and New Energy Technology, Collaborative Innovation Center of Advanced Nuclear Energy Technology, Key Laboratory of Advanced Reactor Engineering and Safety of Ministry of Education, Tsinghua University, Beijing 100084, China (zhouyp@mail.tsinghua.edu.cn)*

Abstract: Fault diagnosis system plays an important role in reactor safety, which can improve the accident response capability and the safety of the reactor. The multi-level flow model is applied to the fault diagnosis of High-temperature gas-cooled reactor. Some basic concepts and operations of Causal Dependency Matrix (CDM) are introduced for state expression and state propagation based on MFM. The MFM symbols using CDM for MFM model are constructed with Simulink/MATLAB software. The fault diagnosis system was verified by the case of accidental acceleration of helium circulator trip. The fault diagnosis method can accurately analyze the system fault and give reasonable explanation.

Keyword: multi-level flow model; fault diagnosis; HTR-PM; causal dependency matrix

1 Introduction

In the case of failure, the nuclear power plant operator receives hundreds of fault warning signals, and it is difficult for the operator to determine the cause of the failure in a short period of time. Fault diagnosis system is an integral part of the safety system of nuclear power plants, which can effectively improve the operator's ability to handle failures and reduce the probability of human error.

The incomplete expert knowledge base and lack of practical operational data make it difficult to establish a fault diagnosis system for HTR-PM reactors.

In 1990, Linda M expanded the basic concepts of MFM model [1] and realized the graphical modeling based on MFM [2]. Later, Lind attempted to apply MFM to real-time faults of industrial systems Diagnosis [3]. and designed the diagnostic system monitoring interface [4]. On this basis, related technologies and applications based on MFM began to rapidly develop. In 2011, Yun, Z. establish fault diagnosis system based on MFM model for complex distributed systems such as power plants. And they developed intelligent network monitoring and real-time fault diagnosis procedures in C ++ language [5]. In 2012, Zhou Yangping developed a nuclear power plant graphical interface tool based on MFM model and applied it to operator support system for the Monju Plant in Japan [6].2014, 2014, Yang, N. Combine MFM and symbolic directed graph (SDG) to model the nuclear power plant system. The SDG method is used to analyze the graphic symbols in the MFM model, and the alarm analysis completed two fault simulations of the secondary-loop system of the nuclear power plant. The results show that the combination of the two methods can accurately locate the root fault and clearly show the transmission path of the alarm signal [7].

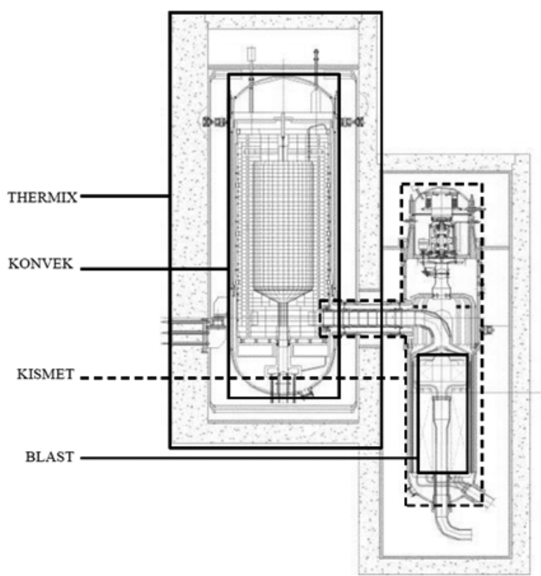

Fig.1 THERMIX package calculation.

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This paper proposes a fault diagnosis method based on Multilevel Flow Modeling(MFM), which builds a hierarchical system structure from the physical components and thermal processes of the system. According to this method, it can reduce the requirement of expert knowledge and operational data and improve the effectiveness of the fault diagnosis system.

2 Fault diagnosis method based on Multilevel Flow Model

2.1 Simulation of HTR-PM

The THERMIX package is a calculation program designed by the Jülich Research Center in Germany [8], for the safety analysis of the High Temperature Gas-cooled Reactor. The THERMIX package consists of five modules. THERMIX module was used to model the core and the main components of the reactor and analyze the transient heat conduction in the r-z two-dimensional cylindrical coordinate. KONVEKSI module analyzes the flow of the coolant gas and solves the distribution of the temperature field, velocity field and pressure field in the reactor according to the distribution of the components. KINSMET module solves the distribution of the temperature field, velocity field and pressure field in the primary loop. BLAST module calculates the flow heat transfer between the helium side, the water side and the pipe wall in the steam generator. KINEX module calculates the power distribution of the reactor core based on the neutron dynamics theory. THERMIX package can simulate the dynamic process of the primary loop system of Modular Pebble Bed Reactor in steady state and various conditions.

The THERMIX package can completing the thermal analysis of the high-temperature gas-cooled reactor-loop system, but the calculation of the reactor is only for the steam generator and does not involve the calculation of the turbine system, the condenser system, the feedwater system, and the control system. To improve the simulation of the whole nuclear power plant, the THERMIX package is embedded into the vPower simulation software to complete the construction of the reactor system. The vPower emulation software was developed by Beijing NEOSWISE Co., Ltd. [9]. The built-in module library includes two-loop systems and common components of the control system for graphical modeling.

Table 1 Simulation in 100% power operating condition.

Parameter	Design Value	Simulation Value	Relative Error
Power(MW)	250.0	250.4	0.16%
Helium Pressure(MPa)	7.0	6.98	0.29%
Helium Mass Flow(kg/s)	96.0	96.0	0%
Helium Inlet Temperature(℃)	250.0	252.7	0.27%
Helium Outlet Temperature(℃)	750.0	752.0	1.25%
Feedwater Flow(kg/s)	96.0	94.8	1.76%
Feedwater Temperature(℃)	205.0	201.4	0%
Outlet Temperature of SG(℃)	571.0	571.0	0.072
Outlet Pressure of SG(MPa)	13.9	13.91	0.42%
Main Steam Temperature(℃)	566	568.4	0%
Main Steam Pressure(MPa)	13.24	13.24	0%
Main Steam Flow(MPa)	186.5	186.5	0.27%

2.2 Multilevel Flow Modeling(MFM)

Multi-level Flow Modeling (MFM) is a graphical functional model method, first proposed in the 1980s, initially not used for fault diagnosis. Later, Lind. M defined the basic concepts of MFM, implemented the graphicalization of the model [1]and then attempted to apply the MFM model in the fault diagnosis system of the industrial control system [2].

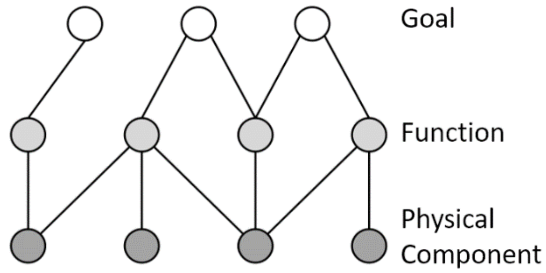


Fig.2 Relations between concepts.

MFM describes the process system by means of goal, physical component and function. Goal indicates the objective or purpose that the system or the sub-system is designed or constructed to achieve. Physical component means what the system or the equipment consists of. Function describes the means by which the physical components achieve the goal. There are three kinds of relations between goal, function, and physical component: realize relation, achieve relation, and condition relation.

MFM model describes the sturcture of system through the interelated flow, including mass flow, energy flow, and information flow. MFM uses graphical symbols to represent the basic concepts of the model which describes the corresponding physical processes with the symbolic language.

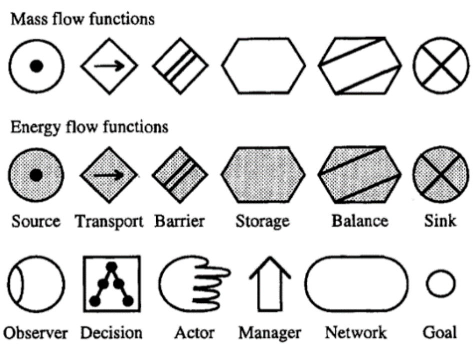


Fig.3 Symbols of multi-level flow model.

2.2 Causal Dependency Matrix(CDM)

Since the MFM model represents the process system in a uniform and discrete way, a matrix way, called as Causal Dependency Matrix (CDM) can be adopted to express the causal dependency graph. Some concepts about the causal dependency matrix are explained as following.

A state vector S is applied to express the state of the MFM symbol:

$$S_t = [S_1, \cdots, S_i, \cdots, S_n]; 0 \leq S_i \leq 1 \quad (1)$$

When a component fails, the fault propagates to the other parts of the system to trigger more alarm signals. The signals of the nodes denote high, normal, and low states by N (Normal), H (High) and L (Low), which are expressed as state vectors [1,0,0], [0,1,0] [0,0,1]. For different parts, the meaning of the node state is not the same, such as three states for helium fan are high helium flow, normal helium flow and low helium flow, and three states for the water pump are high water flow, normal waterflow and low water flow.

A state conversion matrix indicates the relations between two contiguous MFM symbols:

$$\boldsymbol{C} = \begin{bmatrix} C_{11} & \cdots & C_{1j} & \cdots & C_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ C_{i1} & \cdots & C_{ij} & \cdots & C_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ C_{n1} & \cdots & C_{nj} & \cdots & C_{nn} \end{bmatrix}; 0 \leq C_{ij} \leq 1 \quad (2)$$

By using state vectors and state conversion matrixes, the consequence analysis of MFM model can be carried out with simple matrix operations. The fault is propagated along the MFM model structure. Fault propagation may be forward or backward. The forward propagation process is expressed as a forward fault propagation matrix $\boldsymbol{C}_f$, and the propagation process in the reverse direction is expressed as a backward propagation matrix$\boldsymbol{C}_b$. The state of a MFM symbol can be predicted according to the state of its contiguous symbol and the forward/backward fault propagation matrix between them. As the Eq.(3) shown, $\boldsymbol{S}$ is the state of the node, $\boldsymbol{S}_b$ is the state of backward node, $\boldsymbol{S}_f$ is the state of forward node, $\boldsymbol{S}_b$

$$\boldsymbol{S}_b = \boldsymbol{S} \times \boldsymbol{C}_b; \boldsymbol{S}_f = \boldsymbol{S} \times \boldsymbol{C}_f \quad (3)$$

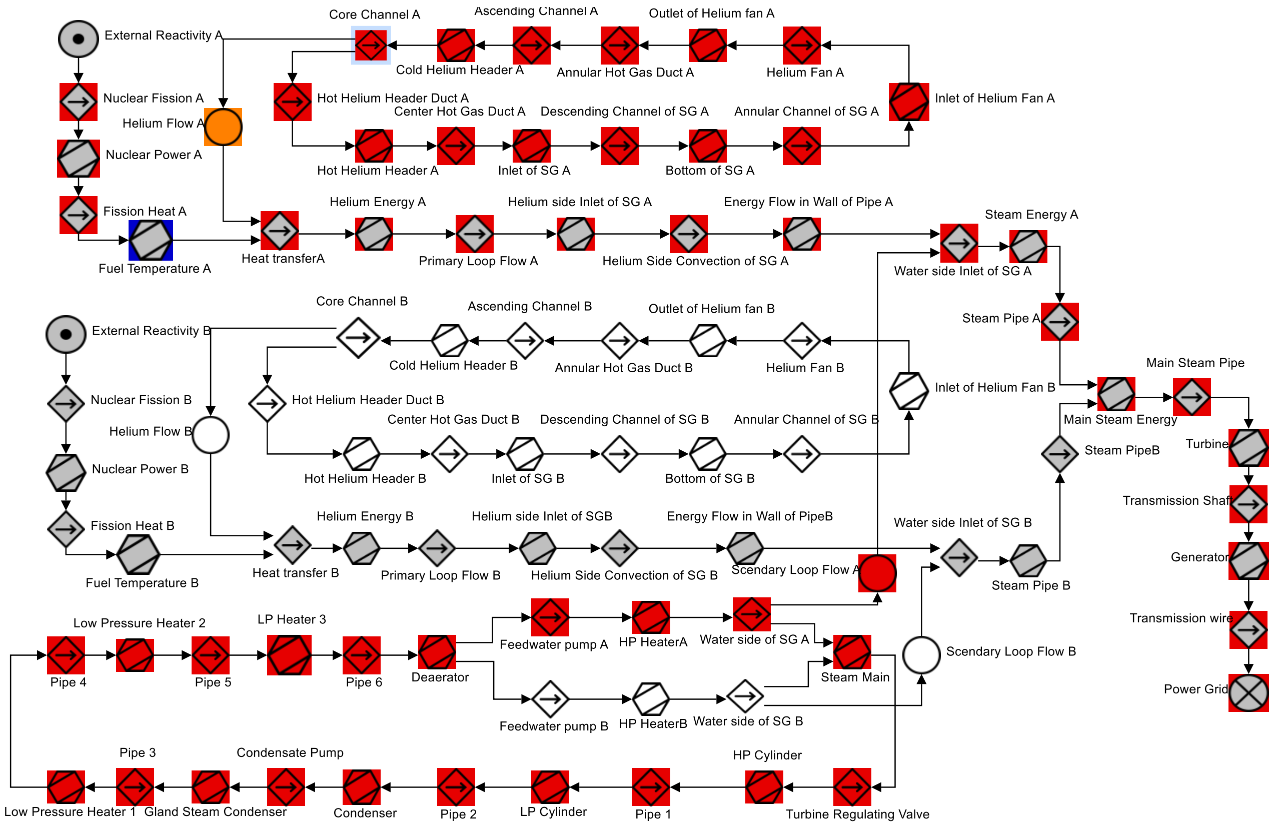


Fig.4 Fault propagation path.

The derivation of the fault propagation causal matrix mainly depends on the concepts of MFM symbols. For some specific components, the causal matrices are established by the principles of conservation equations, control strategy and expert experience. The causal dependency matrix is related to the state of the system. The causal relationship between the nodes will change with the specific circumstances. In this paper, we study the fault propagation under the fixed causal matrix. For the practical application, different propagation matrices should be established according to different rules, and the fault diagnosis system will change the causal dependency matrix in different states of the system.

3 A test case on HTR-PM

Simulink/MATLAB software allows users to create custom module libraries and add user-defined variable parameters. With the custom module function, create a MFM module library for graphical modeling. In the Simulink platform, we create a graphics module for each MFM symbol concept and the algorithm is packaged into the module. In the MFM fault diagnosis, we only need to select the corresponding module and connect the module according to the multilevel flow model to complete the MFM model.

As the Fig.4 shown, MFM model was constructed based on HTR-PM plant and the off-line signal/state files for difference fault cases, the Simulink software can act as a demonstration diagnosis system. The “Helium fan accidental acceleration” case was tested using the demonstration diagnosis system.

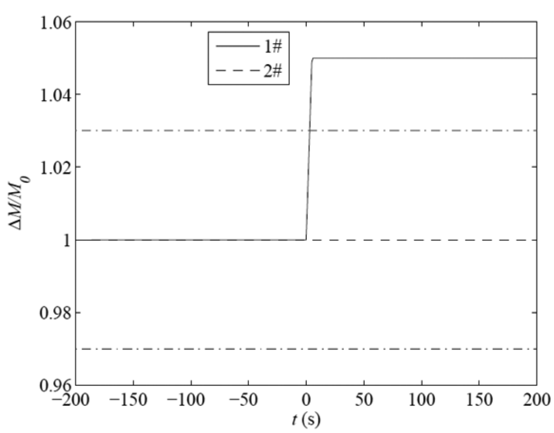


Fig.5 Helium mass flow rate.

The Fig.5 shows the helium mass flow rate over time. At the initial moment the mass flow of the reactor is in a steady state. After the fault occurs, it can be observed that the helium flow rate in the No. 1 reactor rises stepwise.

The increase in helium flow will affect the heat transfer in the reactor core. Figure 6 shows the temperature difference between hot and cold helium over time. The increase in mass flow rate leads to a decrease in the temperature of the outlet helium flow. Then the temperature difference between the hot and cold helium is reduced, resulting in a decrease in the reactor core temperature. The drop of temperature will introduce a positive reactivity, resulting in an increase

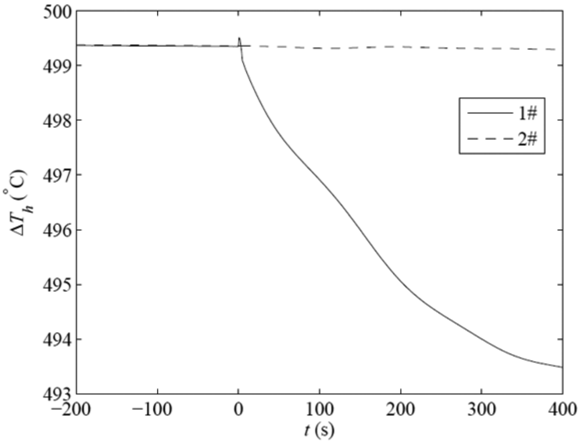


Fig.6 The temperature difference between hot and cold helium.

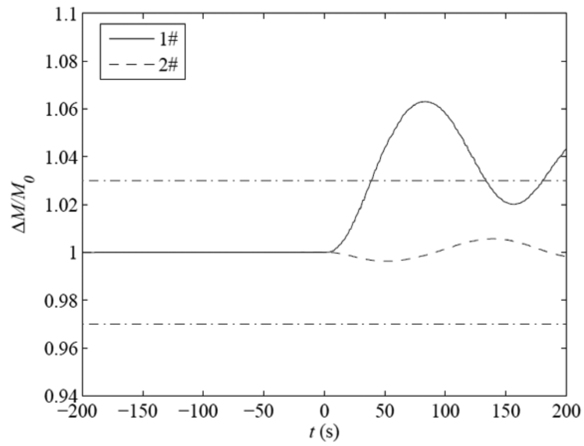


Fig.7 The feed water flow.

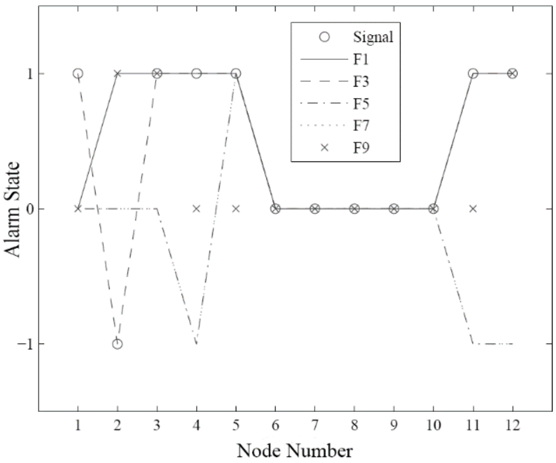
At the same time, the helium flow takes more heat from the reactor. In the steam generator, the helium side will release more energy to the water side, causing the control system to respond. Then, the feed water flow, the steam flow, and the main steam energy increases. It can be observed in Fig.7 that, after the introduction of the fault, the water supply system of the No. 1 reactor is automatically adjusted and the feed water flow is increased.

The helium fan causes a high value alarm of helium flow in the primary loop system and the core fuel temperature is at a low value alarm. The fault is transmitted to the secondary loop, resulting in a high value alarm in the flow of the secondary circuit and a rise in power of the turbine.

When the alarm signal appears, the fault diagnosis system starts the fault reasoning, and all alarm signal is received after about 40 seconds. The fault diagnosis system also gives the fault propagation path, as shown in Fig 4. The red symbols in the figure represents the high value alarm and the blue ones represent low value alarm.1 # reactor helium fan accelerates, resulting in a high flow alarm for a stream of mass flow. The high flow alarm of the primary loop affects the energy flow through the convective heat transfer process resulting in the fuel core temperature drop. The temperature drop introduces positive reactivity, and the reactor power increases. As the energy flow changes, the fault propagates to the secondary loop. Under the action of the control system, the flow rate of the secondary loop increases and the main steam flow increases. The main steam energy brings more energy, which leads to the increase of the steam turbine power.

The fault diagnosis system matches the actual alarm signal with the alarm signal obtained by reasoning. As shown in Fig.8, after matching, in different signal nodes, only the alarm state in the case" Accidental acceleration of helium fan" matches the alarm state of actual signal. So we can give the correct diagnosis.

The fault diagnosis system indicates the propagation path of the alarm. The red sign indicates that the node is at the alarm high value and the blue node is at the alarm low value. It is also observed from the fault propagation path that the accidental acceleration of the helium fan causes a series of high alarm values in the loop system and the core fuel temperature is at a low alarm level. The fault is transmitted to the secondary circuit, resulting in an increase in the flow of the secondary circuit, a high alarm value, and a rise in power in the turbine.



F1——Reactor power increases
F3——accidental acceleration of Helium fan
F5——accidental acceleration of feed pump
F7——Default value error of temperature controller
F9——The HP cylinder extraction steam off

Fig.8 Signal and diagnosis results.

4 Conclusion

A method for consequence analysis based on MFM, named as Causal Dependency Matrix (CDM), was proposed to express and propagate the alarm states of MFM symbols under fault situation with matrix operations. By using Simulink/MATLAB software, the basic symbols were constructed and applied to model the HTR-PM plant based on MFM. A demonstration system by loading the MFM model and offline signal/states file was used for successful diagnosis of the fault cases, which indicated the feasibility of the proposed CDM method.

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