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Qualitative Simulator for Estimation of Plant Behaviour during Abnormal Situation

by

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Abstract

A simulator which can qualitatively estimate the plant behaviour during abnormal situation is developed. The structure of the plant is viewed as an assembly of units and valves. The concepts of "state of flow in the unit" and "state of valve" are introduced for representing faults and actions to be taken by an operator. Three types of simulation are defined according to the changes in the state of flow in order to estimate the state of the unit qualitatively.

Keywords: Qualitative simulator, Abnormal situation, Estimation

Introduction

In a chemical plant, when an abnormal situation arises, the operator needs to identify the origin of failure. Several fault diagnosis systems are available but they can only identify the origin of failure and so they still depends on the operator to decide the action to be taken. Since so many accidents have been caused by operator's misjudgments or misoperations, there is a need to develop a system which can also suggest appropriate action to be taken when a failure occurs.

Such a system requires information on plant behaviour during abnormal situation. This is not necessarily quantitative but may be qualitative. In particular, it is necessary to know whether normal operation is resumed or whether the abnormal situation continues or there is an accident as a result of taking action.

The purpose of the present work is to develop a simulator which can qualitatively estimate the state of a chemical plant arising from action to be taken by an operator as a consequence as abnormal condition. In the present work, the following faults are considered: Blockage in a pipeline, Leakage from a pipeline, Leakage from a tank, Malfunction of a pump, Misoperation of a valve. With respect to the actions taken when the above mentioned fault occurs, these are classified as Operation of a valve, Starting a pump and Stopping a pump.

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1. Qualitative Representation of a System and Its State

1.1 State of Flow and State of Valve

For convenience, the following assumptions are adopted with respect to faults and actions.

1) Fluid does not flow through the pipeline which is blocked.
2) Reduced fluid flows from the pipeline or tank which leaks.
3) Operation of valves is limited to a condition: open to closed or closed to open.

The flow of fluid in a plant changes arising from faults or actions under these assumptions, so it is very useful to introduce the concept of "state of flow" proposed by O'Shima[1]. The following four states can be defined for a unit which is a portion of a plant isolated by valves, and can comprise any items of equipment.

FLOW : Fluid flows through the unit. Both the inlet and outlet valves are open.
BLOCK : Fluid is retained in the unit. All outlet valves are closed but an inlet valve is open.
BRANCH : Fluid does not flow in the unit. All inlet valves are closed but an outlet valve is open.
TRAP : Fluid is trapped in the unit. All inlet and outlet valves are closed.

The state of flow in the unit is determined by the apertures of the inlet and outlet valves (open or closed). In abnormal situations, a fluid may not flow, even when both the inlet and outlet valves are open (for example, when there is a blockage of a pipeline); there is also the case of fluid flow, even when all the inlet valves or all the outlet valves are closed (for example, when there is a leakage of a pipeline).

In such circumstances, the state of a valve is defined by using three elements. Each element can have the following values:

Aperture of valve
OPEN (O) : Valve is open.
CLOSE (C) : Valve is closed.

Condition of valve
NORMAL (N) : Fluid flows in the line according to the valve aperture.
IMAGINARY-CLOSED (IC) : Fluid does not flow in the line, in spite of a valve aperture (i.e. corresponds to a closed valve).
IMAGINARY-OPEN (IO) : Fluid flows in the line, in spite of a valve aperture (i.e. corresponds to an open valve).
SWITCH-OFF-CLOSED (SOC) : Fluid does not flow in the line, in spite of a valve aperture because the pump is stopped (i.e. corresponds to a closed valve). When the pump is started, fluid flow in the line depends on the valve aperture.

Type of valve
MANUAL (M) : Manual.
CONTROL (CR) : Control.
IMAGINARY (I) : Imaginary.
LEAK (L) : Imaginary valve for tank leakage.

1.2 Representing Faults and Actions

Faults and actions should correspond to the changes in the state of valves following

Table 1 Representation of faults.

Fault	State of Valve Before	State of Valve After	Influence
Misoperation of valve	(O N M)	(C N M)	FLOW-DECREASE
	(C N M)	(O N M)	FLOW-INCREASE
	(O/C SOC M)	(C/O SOC M)	NON-INFLUENCE
	(O N CR)		NON-OPERATION
	(O/C N/SOC I)		NON-OPERATION
	(C N L)		NON-OPERATION
Blockage of pipeline	(O N M/CR/I)	(O IC M/CR/I)	FLOW-DECREASE
	(C N M/CR/I)	(C IC M/CR/I)	NON-INFLUENCE
	(O/C SOC M/CR/I)	(O/C IC M/CR/I)	NON-INFLUENCE
	(C N L)		NON-EXISTENCE
Leakage from pipeline (upstream side of valve)	(O N M/CR/I)	USU: (O IO M/CR/I)	FLOW-INCREASE
		DSU: (O IC M/CR/I)	FLOW-DECREASE
	(C N M/CR/I)	USU: (C IO M/CR/I)	FLOW-INCREASE
		DSU: (C IC M/CR/I)	NON-INFLUENCE
	(O/C SOC M/CR/I)	USU: (O/C IO M/CR/I)	FLOW-INCREASE (DSU = PUMP) NON-INFLUENCE (DSU = PUMP)
		DSU: (O/C IC M/CR/I)	NON-INFLUENCE
	(C N L)		NON-EXISTENCE
Leakage from pipeline (downstream side of valve)	(O N M/CR/I)	USU: (O N M/CR/I)	FLOW-INCREASE
		DSU: (O IC M/CR/I)	FLOW-DECREASE
	(C N M/CR/I)	USU: (C N M/CR/I)	NON-INFLUENCE
		DSU: (C IC M/CR/I)	NON-INFLUENCE
	(O SOC M/CR/I)	USU: (O N M/CR/I)	FLOW-INCREASE
		DSU: (O IC M/CR/I)	NON-INFLUENCE
	(C SOC M/CR/I)	USU: (C N M/CR/I)	NON-INFLUENCE
		DSU: (C IC M/CR/I)	NON-INFLUENCE
	(C N L)		NON-EXISTENCE
Malfunction of pump	(O N M/CR/I)	(O IC M/CR/I)	FLOW-DECREASE
	(C N M/CR/I)		NON-EXISTENCE
	(O/C SOC M/CR/I)		NON-EXISTENCE
	(C N L)		NON-EXISTENCE
Leakage from tank (outlet valve only)	(O N M/CR/I)	(O IC M/CR/I)	FLOW-DECREASE
	(O SOC M/CR/I)	(O IC M/CR/I)	NON-INFLUENCE
	(C N/SOC M/CR/I)	(C IC M/CR/I)	NON-INFLUENCE
	(C N L)	(O N L)	FLOW-INCREASE

O : OPEN N : NORMAL M : MANUAL
C : CLOSE IC : IMAGINARY-CLOSED CR : CONTROL
IO : IMAGINARY-OPEN I : IMAGINARY
SOC : SWITCH-OFF-CLOSED L : LEAK
USU : upstream unit of valve
DSU : downstream unit of valve

deviations in system variables. The faults are represented in the **Table 1**. The valve between the upstream unit (USU) and the downstream unit (DSU) has the state of the outlet valve for USU, which is usually the same as that for DSU inlet valve. In the pipeline leakage, the states of valves for USU and DSU are separately defined, because the USU flowrate increases because of the leakage while that for DSU decreases. Changes in the state of flows in USU and DSU are considered separately. There are two situations, according to whether the leakage happens upstream of the valve (USV) or downstream (DSV). When the leakage occurs in the USV, the influence of leakage on USU cannot be removed by closing the valve. However, when the leakage occurs in the DSV, the influence of leakage on USU can be removed by closing the valve.

1.3 Qualitative Modeling of Unit

A variable X in a unit is assumed to take only three values:

$$X=\begin{cases} + & \text{high} \\ 0 & \text{normal} \\ - & \text{low} \end{cases} \qquad (1)$$

Table 2 Method for estimation.

Case	Present value of X	Increment x of X	New value of X
1	+	+	+
2	+	0	+
3	+	−	0?
4	0	+	+
5	0	0	0
6	0	−	−
7	−	+	0?
8	−	0	−
9	−	−	−

Table 3 Estimation of the value 0?.

Case	Present value of X	Increment x of X	Sbu-increment x'	New value of X
1	+	−	+	−
2	+	−	0	0
3	+	−	−	+
4	−	+	+	+
5	−	+	0	0
6	−	+	−	−

The increment x of X is also assumed to take only three values:

$$x=\begin{cases} + & \text{increase} \\ 0 & \text{hold} \\ - & \text{decrease} \end{cases} \tag{2}$$

Given the present value of X and an increment x, a new value of X can be determined using **Table 2**. The value 0? means that the new value of X cannot be determined uniquely, but depends on the magnitude of x. The sub-increment x' corresponding to the magnitude of x is introduced in order to determine the new value of X.

$$x'=\begin{cases} + & \text{large} \\ 0 & \text{medium} \\ - & \text{small} \end{cases} \tag{3}$$

A new value of X is then determined by **Table 3**. The behaviour of unit is determined by estimating values of the increments and sub-increments, arising from the known initial value of X.

2. Qualitative Simulator

2.1 Classification of Simulation

The unit which is directly influenced by fault or action is called "TOP-UNIT". Three types of simulation are defined according to the change in state of flow in the TOP-UNIT. Normal simulation. The state of the TOP-UNIT is changed by the fault or action when the state of flow in the TOP-UNIT is changed to one of the following:

FLOW → FLOW FLOW → BRANCH FLOW → BLOCK
BRANCH → FLOW BLOCK → FLOW

The simulation starts with the TOP-UNIT using the method mentioned in previous

Table 4 Condition of state of flow.

Estimated Unit	Following Unit upstream	downstream
FLOW	FLOW	FLOW
BRANCH		BRANCH or FLOW
BLOCK	BLOCK or FLOW	

Table 5 Condition of state of flow.

Estimated Unit	Following Unit upstream	downstream
BRANCH	BRANCH	
BLOCK		BLOCK

section and is sequentially applied to the units which are connected to the TOP-UNIT through a valve which is set open. These units satisfy the condition given in **Table 4** because of the state of the flow. When the unit does not satisfy the condition, the state and state of flow in it are not changed by the fault or action, even if it is connected to the TOP-UNIT through an open valve.

Change simulation. The state of the TOP-UNIT is not changed by the action but according to the state of flow in the TOP-UNIT as follows:

TRAP → BRANCH TRAP → BLOCK

The state of the TOP-UNIT is a result of the fact that flowrate through the inlet valve decreases when the state of flow in the TOP-UNIT is BRANCH; and the flowrate through the outlet valve decreases when the state of flow in the TOP-UNIT is BLOCK. As in Normal simulation, it starts with the TOP-UNIT, and is sequentially applied to the units which are connected to the TOP- UNIT through the valve which is set open according to the condition given in **Table 5**.

Hold simulation. The state of the TOP-UNIT is held when the state of flow in the TOP-UNIT changes to one of the following:

BRANCH → TRAP BLOCK → TRAP TRAP → TRAP
BRANCH → BRANCH BLOCK → BLOCK

2.2 Case of two TOP-UNITs

When there are two TOP-UNITs for fault or action, the state of flow in units is determined in the following manner:

1) Units are divided into two groups, which are upstream units from upper side TOP-UNIT and downstream units from lower side TOP-UNIT.
2) The above-mentioned methods of simulation are applied for each group.

If it possible to consider the propagation speeds of the influence of faults or actions, then orders of the units are determined in a recycle or a bypass.

2.3 Treatment of Control System

It is assumed that the control system automatically selects the action (in general, operation of control valve) for an abnormal value of the controlled variable. This is not the same as operation of manual valve. The control system is analyzed as below:

1) The effect of the control action is considered when the controlled variable shows an

abnormal value during simulation.

2) When the controlled variable cannot reach a normal value, the state of the control valve is estimated and simulation is continued.
3) When the controlled variable is normal, it is not necessary to predict the behaviour of the controlled variable and the simulation is continued. The state of the control valve is estimated and the control action is registered.
4) If a control action is registered after finishing the simulation, a simulation for the control action (Control simulation) is carried out.

2.4 Structure of the Simulator

There are three kinds of data and three kinds of system in the simulator.

Database A. Database A gives information about the type of unit i.e. a common structure of units which belong to the same type, and common rules applied to the units.

Database B. Database B describes the states of the individual units and the relation of the connections between the units.

Knowledge base. The knowledge base stores the following production rules.

1) Rules for setting the initial value of increment for the variable.
2) Rules for estimating the increment in the variable.
3) Rules for selecting an action.

Frame operating system. This system deals with Databases A and B described by a so-called frame.

Production system. The production system operates by the use of rules in the Knowledge Base.

Command system. This system is the interface between a user (operator) and the simulator and deals with commands given by the user which then operates on the above sub-systems.

3. Application

The simulator proposed by the present work has been applied to the pressure control system shown in **Fig. 1** in order to evaluate its usefulness. **Figure 2** shows the representation of the system in terms of units.

The four actions listed in **Table 6** are taken sequentially because of the fault caused by

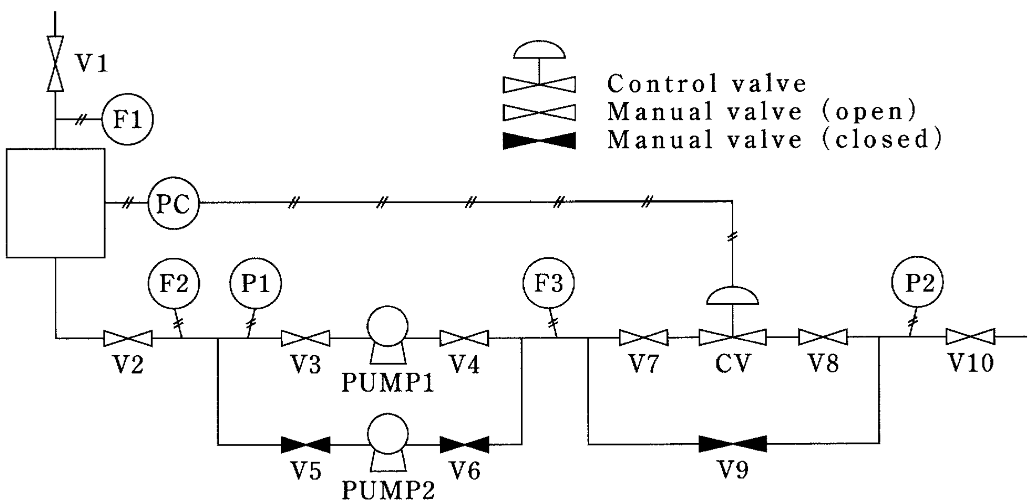
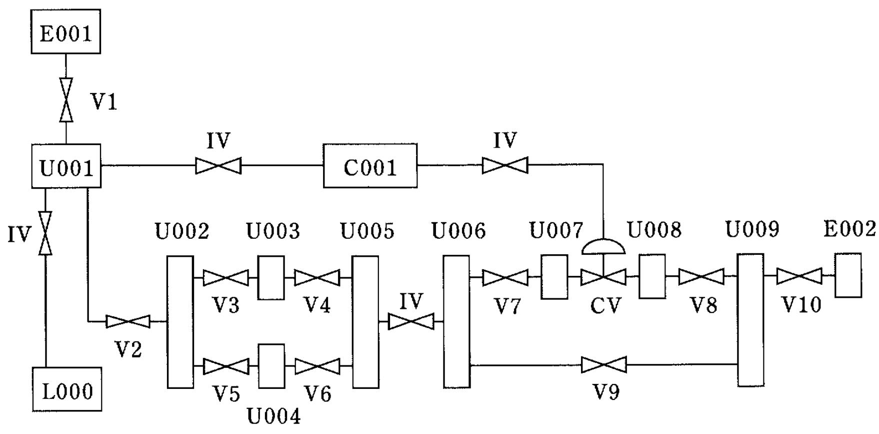


Fig. 1 Pressure control system as an example.



U001 : Tank
U002 , U006 : Pipeline (1 inlet , 2 outlets)
U005 , U009 : Pipeline (2 inlets , 1 outlet)
U007 , U008 : Pipeline (1 inlet , 1 outlet)
U003 , U004 : Pump
C001 : Pressure controller
E001 , E002 : Environment
L000 : Environment (for leakage)
V1-V10 : Manual valve
CV : Control valve
IV : Imaginary valve

Fig. 2 Representation of the system shown in **Fig. 1** in terms of units.

Table 6 List of actions.

Action Name	Operation
ACTION1	Close the valve V1
ACTION2	
ACTION2-1	Switch off PUMP1
ACTION2-2	CLose the valve V3
ACTION2-3	Close the valve V4
ACTION2-4	Open the valve V5
ACTION2-5	Open the valve V6
ACTION2-6	Switch on PUMP2
ACTION3	Open the valve V2
ACTION4	Open the valve V1

closing the valve V2 (misoperation of valve). ACTION2 is a series of actions which are dealt with together because the series makes sense as an overall action. **Table 7** gives the transition in the value of measurements.

Though the pressure in the tank will rise after closing the valve V2 so as to decrease the outlet flowrate of tank, the effect of the control action does not appear, even if the control valve is fully open. The abnormal state of the system continues when ACTION1 is taken and even when ACTION2 a correct action for the malfunction of PUMP1 is taken. ACTION 3 is a correct action for the fault. Nevertheless, the pressure in the tank has the tendency to become '−' because of ACTION1, which is misoperation. The tendency is compensated for by the control action which closes the control valve so as to decrease the outlet flowrate from the tank. The normal state of the system is recovered when ACTION4 is taken so as to remove the influence of ACTION1. Then, the tendency of the pressure in the tank to become '+' is compensated for the opening the control valve to its normal position.

The simulator was developed in the Common Lisp computer language to run on the Data General in the Department of Chemical Engineering, Leeds university. The above-mentioned example was finished within a few minutes.

Table 7 Transition of values of measurements.

Fault or Action	Measurements F1	PC	F2	P1	F3	P2
Initial value	0	0	0	0	0	0
FAULT	−	+	−	−	0	0
	−	+	−	−	−	0
	−	+	−	−	−	−
ACTION1	−	+	−	−	−	−
ACTION2-1	−	+	−	−	−	−
ACTION2-2	−	+	−	−	−	−
ACTION2-3	−	+	−	−	−	−
ACTION2-4	−	+	−	−	−	−
ACTION2-5	−	+	−	−	−	−
ACTION2-6	−	+	−	−	−	−
ACTION3	−	−	0	0	−	−
	−	−	0	0	0	−
	−	−	0	0	0	0
CONTROL	−	−	0	0	−	−
	−	−	−	+	−	−
	−	0	−	+	−	−
ACTION4	0	+	−	+	−	−
CONTROL	0	+	−	+	0	0
	0	+	0	0	0	0
	0	0	0	0	0	0

Conclusions

A simulator which qualitatively estimates the state of a chemical plant when an operator takes action during an abnormal situation is proposed. The task of user is only to give the data about the relations connecting units after defining the representation of a plant in terms of units. This corresponds to the Database B, because the simulator has data relating to types of unit (Database A) and the rules applied to the units (Knowledge Base). Although reaction and separation processes have not yet be considered, the simulator is basically applicable.

References

1) O'Shima,E.; J. of Chem. Eng. of Japan, Vol. 11, pp.390 (1978)