ACTUATOR AND COMPONENT FAULT ISOLATION IN A FLUID CATALYTIC CRACKING UNIT[1]

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Abstract: This paper considers an observer-based approach for detection and isolation of actuator and component faults in a Fluid Catalytic Cracking (FCC) unit. Model based analytical redundancy is used on an augmented linearised model of the non-linear FCC unit to the isolation of faults. Some component faults are modelled and implemented in a software package to show the considered approach. The proposed design is tested using a non-linear simulation of the FCC unit model. The results show that the linear observer-based approach applied to an augmented state of the FCC to actuator and component fault detection and isolation can be used with success even if the non-linear behaviour of the FCC has some effect on the residuals. *Copyright© 2005 IFAC*

Keywords: Linear model, observers, fault detection and isolation.

1. INTRODUCTION

The petroleum industry is one of the major productive in the world. In this context an important process after extraction is the refining procedure, where petroleum is transformed in to several useful products. A Fluid Catalytic Cracking Unit (FCCU) is a key process in petroleum refining for upgrading heavy hydrocarbons to more valuable lighter products (such as gasoline and LPG). The FCC unit is a critical component in a refinery. Even small increase in efficiency pays important dividends because of the large amounts of oil handled. It is a slow and multivariable process with highly non-linear dynamics and strong interactions among its variables. The opportune detection and isolation of faults allows to improve the safety and reliability of industrial processes. In a complex process, such as FCC unit, fault diagnosis is very important in order to avoid dangerous situations.

Fault diagnosis techniques have been studied intensively in the past 30 years, as can be seen in (Basseville, 1997), (Frank *et al.*, 2000), (Kinaert, 2003) as well as in (Chen and Patton, 1999; Patton *et al.*, 2000). Analytical redundancy approaches make use of measurement, which are commonly used to control, and the mathematical model of the process.

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The FCC Unit Kellog Orthoflow F reactor / regenerator (Moro and Odloak, 1995) is the process under consideration. In the context of fault detection, the FCC unit has been studied previously. In (S. Dash G. V. Reklitis V. Venkatasubramanian, 2000), a Fault Detection and Isolation (FDI) scheme for a discretized version of the AMOCO Model IV FCCU based on an extended Kalman filter is presented. In this case only two component faults were considered. In (Heim *et al.*, 2001), a different FDI scheme based on a causal and heuristic approach has been applied to a FCC pilot process. In (Heim *et al.*, 2003) te application of several causal and knowledge based models to FDI in the FCC has been considered. Recently an approach to FDI in the FCC unit using observer-based residuals has been proposed in (Leon-Canton *et al.*, 2004) for 4 component faults and in (Sotomayor *et al.*, 2004) for 4 sensors and 4 actuator faults. The approach of Sotomayor, et. al 2004 considers a reduced order model obtained by subspace identification techniques.

In this work an observer-based approach to fault diagnosis to the FCCU Kellog Orthoflow F reactor/regenerator is proposed. Different to the approach in (Leon-Canton *et al.*, 2004) only one observer (not a bank of observers) is required. Six faults were considered. The result is reached using an augmented state and designing an observer for this system. Note that a simulation using the non-linear model of the FCC is considered. With the proposed approach is possible to detect and isolate all the studied component faults. The proposed of this paper could be considered as a continuation of the results presented in (Alcorta-García *et al.*, n.d.)

The paper is organized as follows: section 2 reviews the observer based method to FDI and presents the problem; in section 3 the model considered of the FCCU is presented; the developed scheme to fault diagnosis of the FCC is shown in section 4; section 5 shows some simulation results and the conclusions are presented in section 6.

2. PRELIMINARIES

Some required concepts to be used in the paper are discussed in this section.

2.1 Observer-based approach to FDI

Model-based Fault Detection and Isolation use analytical redundancy (and not physical redundancy) in order to obtain fault signed signals, which are called residuals. See figure 1. Further, the residuals requires to be evaluated in order to detect a fault.

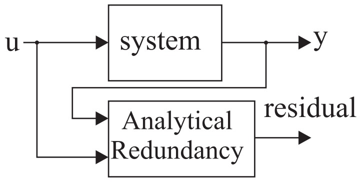

Fig. 1. Analytical redundancy for FDI

There are different ways to generate analytical redundancy, but only the observer-based approach will be considered here. The observer-based approach is based on a mathematical model of the system, which is used to obtain an estimate of the nominal (fault free) output of the system. A residual could be defined as the difference between the actual (measured) and the nominal (fault free) output. This is shown in figure 2. The residual evaluation required for FDI could e realized by a signal norm (Ding and Frank, 1991), and a threshold should be defined as well. In this work,the residual evaluation is defined by the sum of the absolute value of the residuals in a time window of length ν:

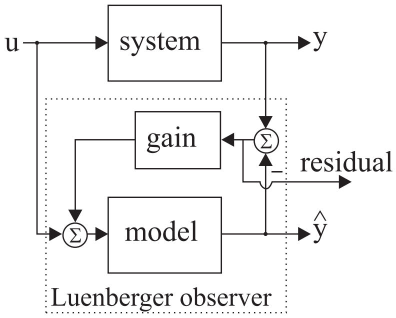

Fig. 2. Basic observer-based approach to FDI

$$\Omega(r_k) = T\sum_{i=1}^{\nu} \omega_{k-i}|r_{k-i}| \tag{1}$$

The idea to weighting the contribution of the residual at each instant k is to give more value to the newest residuals. In this way the evaluation function would respond fast to a fault. Besides the evaluation function $\Omega(\cdot)$, a threshold is required to take a decision about the presence of a fault (Ding and Frank, 1991).

The time window length ν as well as the weights ω_i have been selected in order to be sure that there is no false alarms when no fault is presented.

2.2 Problem formulation

Consider a non-linear system given by

$$\begin{aligned} \dot{x}(t) &= f(x(t), u(t), \theta, d(t)) \\ y(t) &= h(x(t), u(t), \theta) \end{aligned} \tag{2}$$

where $x(t) \in \Re^n$ is the system state, $u(t) \in \Re^p$ is the input vector, $y(t) \in \Re^m$ is the output vector of the system, $\theta \in \Re^l$ represents the actual system vector of parameters (If no faults $\theta = \theta_0$, with θ_0 is the nominal vector parameters).

Problem *Given the system (2) find a residual generator $r(t)$ of the form:*

$$\begin{aligned} \dot{z}(t) &= g(z(t), y(t), u(t), \theta_0) \\ r(t) &= R(z(t), y(t), u(t), \theta_0) \end{aligned} \tag{3}$$

and a threshold $th(y(t), u(t), \theta_0)$ which satisfy the following inequalities

$$\begin{aligned} r(t) \le th \quad &\Leftrightarrow \quad \theta = \theta_0 \\ r(t) > th \quad &\Leftrightarrow \quad \theta \neq \theta_0 \\ r_i(t) \le th_i \quad &\Leftrightarrow \quad \theta_i = \theta_{i0} \end{aligned}$$

△△△

3. THE FLUID CATALYTIC CRACKING UNIT

The FCCU is described by a set of 26 non-linear differential equations and 74 algebraic relations (Moro and Odloak, 1995). The differential equations related with the FCCU reactor are:

$$\begin{aligned} \frac{dT_{rx}}{dt} &= \frac{\frac{1}{1440}(S_f(T_{fp} - T_{rx}) - DH_{fv})R_{tf}D_{tf}}{S_cH_{ris}} + \\ &\quad S_cR_{rc}(T_{rg2} - T_{rx}) - DH_{cr}R_{oc} \end{aligned} \tag{4}$$

$$\frac{dH_{ra}}{dt} = R_{rc} - R_{sc} \tag{5}$$

$$\frac{dC_{cat}}{dt} = \frac{-R_{rc}C_{cat} + 100R_{cf}}{H_{ra}} \tag{6}$$

$$\frac{dC_{sc}}{dt} = \frac{R_{rc}(C_{rc2} - C_{sc}) + 100R_{cf}}{H_{ra}} \tag{7}$$

Differential equations for the first stage of the regenerator:

$$\frac{dH_{rg1}}{dt} = R_{sc} - R_{rc1} \tag{8}$$

$$\begin{aligned} \frac{dC_{rc1}}{dt} &= \frac{R_{sc}(C_{sct} - C_{rc1})}{H_{rg1}} - R_{cb1} - 0.012DH_{cb1}Carb_1 \\ &\quad +0.0215S_aR_{ar1}(T_{ra} - F_{ar12}T_{rg1}) \end{aligned} \tag{9}$$

$$\frac{dT_{rg1}}{dt} = \frac{S_cR_{sc}(T_{ra} - T_{rg1}) - 0.001F_{g1}S_aT_{rg1}}{H_{rg1}S_c} \tag{10}$$

$$\frac{dO_{fg1}}{dt} = \frac{21Rm_{ar1} - F_{gm1}O_{fg1} - 100Carb_1fator_1}{V_1rho_1} \tag{11}$$

$$\frac{dO_{d1}}{dt} = \frac{F_{gm1}(O_{fg1} - O_{d1}) - 3000R_{co}\_1V_{d1}}{V_{d1}rho_{d1}} \tag{12}$$

$$\frac{dT_{d1}}{dt} = \frac{F_{g1}S_a(T_{rg1} - T_{d1}) + 0.405 \times 10^7 R_{co}\_1V_{d1}}{V_{d1}rho_{d1}MM_{d1}S_a} \tag{13}$$

Differential equations for the second stage of the regenerator:

$$\frac{dH_{rg2}}{dt} = R_{rc1} - R_{rc} \tag{14}$$

$$\frac{dC_{rc2}}{dt} = \frac{R_{rc1}(C_{rc1} - C_{rc2})}{H_{rg2}} - R_{cb2} \tag{15}$$

$$\begin{aligned} \frac{dT_{rg2}}{dt} &= \frac{0.0215S_a(R_{ar2}T_{ar} + R_{ar1}F_{ar12}T_{rg1})}{H_{rg2}S_c} + \\ &\quad S_cR_{rc1}(T_{rg1} - T_{rg2}) - .012DH_{cb2}Carb_2 \\ &\quad -0.001F_{g2}S_a(0.98T_{rg2} + 0.02T_{ar}) \end{aligned} \tag{16}$$

$$\begin{aligned} \frac{dO_{fg2}}{dt} &= -\frac{100Carb_2fator_2 + F_{gm2}O_{fg2}}{V_2rho_2} \\ &\quad +\frac{21Rm_{ar2}}{V_2rho_2} \end{aligned} \tag{17}$$

$$\frac{dO_{d2}}{dt} = \frac{F_{gm2}(O_{fg2} - O_{d2}) - 3000R_{co}\_2V_{d2}}{V_{d2}rho_{d2}} \tag{18}$$

$$\begin{aligned} \frac{dT_{d2}}{dt} &= \frac{F_{g2}S_a(0.98T_{rg2} + 0.02T_{ar} - T_{d2})}{V_{d2}rho_{d2}MM_{d2}S_a} + \\ &\quad 0.405816 \times 10^7 R_{co}\_2V_{d2} \end{aligned} \tag{19}$$

Differential equations for the dilute phase of the regenerator:

$$\frac{dO_{dg}}{dt} = \frac{F_{gm}(O2_{gm} - O_{dg}) - 3000R_{co}\_gV_{dg}}{V_{dg}rho_{dg}} \tag{20}$$

$$\begin{aligned} \frac{dT_{dg}}{dt} &= \frac{S_a(F_{g1}T_{d1} + F_{g2}T_{d2} - F_gT_{dg})}{V_{dg}rho_{dg}} + \\ &\quad 0.405816 \times 10^7 R_{co}\_gV_{dg}MM_{dg}S_a \end{aligned} \tag{21}$$

The differential equations corresponding to the pressures of the process FCCU are:

$$\frac{dP_{rg}}{dt} = \frac{(F_g - F_{out})R_{atm}(T_{rg} + 273.15)}{V_{rg}MM_{rg}} \tag{22}$$

$$\frac{dP_{circ}}{dt} = \frac{P_{rg} - P_{circ}}{tau\_P_{circ}} \tag{23}$$

$$\frac{dP_{ra}}{dt} = \frac{(R_{oc} - W_{gas})(T_{rx} + 273.15)}{tau\_P_{ra}} \tag{24}$$

$$\frac{dP_{suc}}{dt} = \frac{W_{gas} - W_{comp}}{tau\_P_{suc}} \tag{25}$$

Differential equations related with the valves

$$\frac{da\_TCV}{dt} = \frac{(s\_TCV - a\_TCV)}{tau\_a\_TCV} \tag{26}$$

$$\frac{da\_LCV}{dt} = \frac{(set\_H\_ra - a\_LCV)}{tau\_a\_LCV} \tag{27}$$

$$\frac{da\_PdCV}{dt} = \frac{(set\_D\_pr - a\_PdCV)}{tau\_a\_PdCV} \tag{28}$$

The parameters as well as the algebraic equations could be obtained from (Moro and Odloak, 1995).

3.1 Linearisation

The development of a FDI scheme in this paper is based on a linearised model of FCCU. The linearisation was done with the help of a symbolic software using Taylor expansion at an operation point. The operation point used in the linearisation is given in the Appendix. The linearised system could be rewritten in the standard form as:

$$\delta f \approx \underbrace{\left|\frac{\partial f}{\partial x}\right|_{x_0,u_0}}_{A} \delta x + \underbrace{\left|\frac{\partial f}{\partial u}\right|_{x_0,u_0}}_{B} \delta u$$

3.2 Fault description

The faults considered in this work were suggested by people working directly with the FCC unit. The following situations are considered:

- Fault 1: 10% increase in catalyst density ($gama$). Changes in the physical properties of catalyst can lead to circulation problems. Mechanical failure may cause a loss of fines or catalyst density may change.
- Fault 2: 15% decrease on the weir constant of the first and second stages (K_w).
- Fault 3: 10 % decrease of the air flow at the regenerator R_{ar12}.
- Fault 4: ($u_2(t)$) Change in the position of the regenerate catalyst valve position.
- Fault 5: ($u_3(t)$) Unwanted change in the total oil feed flowrate.
- Fault 6: ($u_4(t)$) Unwanted change in the temperature of the total oil feed.

The parameter deviations were modelled as multiplicative faults in the program, however additive fault representation is used in the linearised model.

4. PROPOSED APPROACH

Consider a LTI system given by

$$\begin{aligned}\dot{\tilde{x}}(t) &= \bar{A}\tilde{x}(t) + \bar{B}u(t) + Ef(t)\\ y(t) &= \bar{C}\tilde{x}(t)\end{aligned} \qquad (29)$$

where $\tilde{x} \in \Re^n$ is the state vector; $u \in \Re^p$ is the input vector; $y \in \Re^m$ is the output vector; $f \in \Re^s$ is the component fault vector. The matrices $\bar{A}$, $\bar{B}$, $\bar{C}$ and E are of appropriated dimensions. Suppose that the time derivative of the fault vector is zero. The state vector $\tilde{x}(t)$ could be augmented as follows:

$$x \triangleq \begin{bmatrix} \tilde{x} \\ f \end{bmatrix} \qquad (30)$$

The corresponding matrices of the augmented system are the following: $A = \begin{bmatrix} \bar{A} & E \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} \bar{B} \\ 0 \end{bmatrix}$, $C = \begin{bmatrix} \bar{C} & 0 \end{bmatrix}$. The augmented system result:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t)\\ y(t) &= Cx(t)\end{aligned} \qquad (31)$$

Lemma 2.1 *Suppose that the pair ($\bar{A}$, $\bar{C}$) from system (29) is detectable. The fault vector f could be estimated from the system (31) if the pair (A, C) is detectable.*

Note that if the condition of lemma 2.1 is satisfied, only one observer will be necessary to detect and isolate the faults in the fault vector f.

Lemma 2.2 *The fault vector f could be estimated from the system (31) with arbitrary dynamics if the pair (A, C) is observable.*

5. APPLICATION EXAMPLE

For the implementation of the FCC the program developed on the basis of (Moro and Odloak, 1995) has been utilized.

5.1 Fault sceneries

The faults described above are introduced into the FCC system. In order to test the proposed approach some cases are considered:

Case	Faults	occ. time	Mag.
1	No fault	-	-
2	$gama$	30 min.	10%
3	K_W	30 min.	15%
4	R_{ar12}	30 min.	10%
5	u_2	30 min.	10%
6	u_3	30 min.	10%
7	u_4	30 min.	10%
8	$gama$,$Rar12$	30,40 min.	same
9	$gama$,$Rar12$,$U4$	30 min.	same

Table 1. Faults sceneries assumed in the FCC

Note that different to (Leon-Canton *et al.*, 2004), with the proposed approach is possible to consider also simultaneous faults, as in case 8 and 9. The reason of that is related to the kind of structured residuals considered.

5.2 Residual design

Based on the information about the number of faults and the kind of structured residuals, four residuals should be designed. The ideal sensitivity of the residuals is given by: $r_1 = r_1(gama)$, $r_2 = r_2(K_w)$, $r_3 = r_3(R_{ar12})$, $r_4 = r_4(u_2)$, $r_5 = r_5(u_3)$, $r_6 = r_6(u_4)$. The residuals were obtained using the approach described in section 4. Note that the condition given in lemma 2.2 is satisfied, i.e. the resulting observer could be designed with arbitrary dynamics.

The simulation is based on the non-linear model of the FCC and the linear observer-based residuals. The faults were implemented as multiplicative ones in the non-linear model of the FCC. The residual generator is obtained from a 30th order observer. The design of the residuals was carried out in continuous time. The process is modelled in such a way that the time scale is given in minutes.

5.3 Simulation results

The different sceneries were simulated. Because of the space in the paper, only some cases will be presented here. The first case correspond to the fault free situation. The residuals caould be found in figure 3. As can be seen, after some time all the residuals converge to zero.

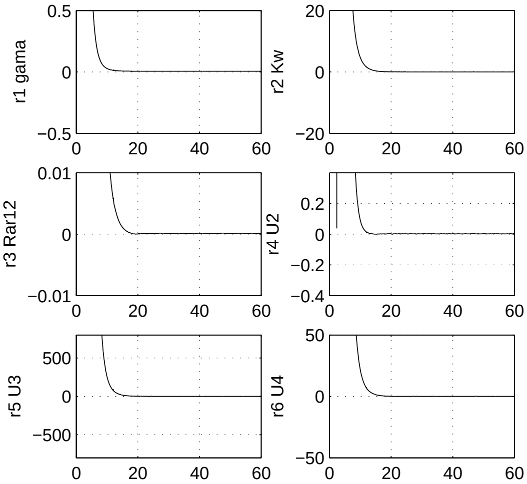

Fig. 3. Fault free residuals.

The second result to be presented is the one with a single gama fault (case 2) at the time $t = 30min$. The results of the residual without evaluation can be found in figure 4. As can be seen from the figure the residuals are not perfect, however using an adequate logic is possible to isolate the fault.

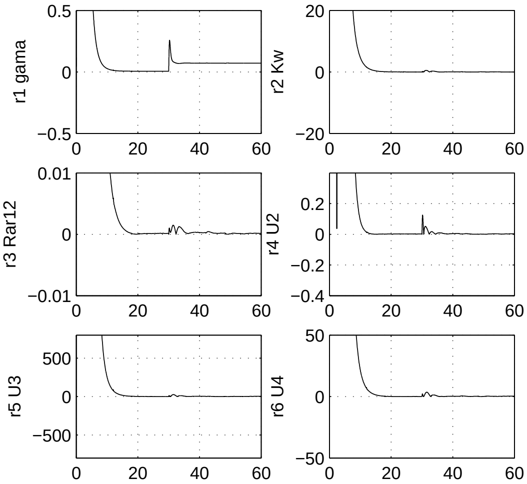

Fig. 4. Residuals for a fault in $gama$ at t=30 min.

The third analysed result correspond to an actuator fault u_3 (case 6). The results can be found in figure 5.

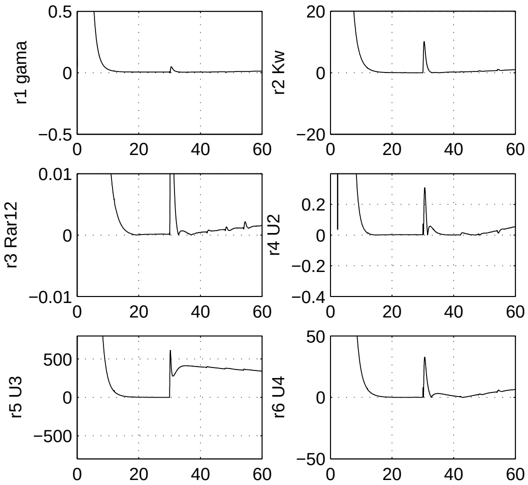

Fig. 5. Residuals for a fault in u_3 at t=30 min.

As can be observed from figure 5, the fault in the actuator u_3 affect more than one residual, however, only one of them is non zero for a long time. This caracteristic could be used for a residual evaluation procedure to isolate the fault.

Tha last result disccused in this work correspond to three simultaneous faults of the case 9. The results could be found in figure 6

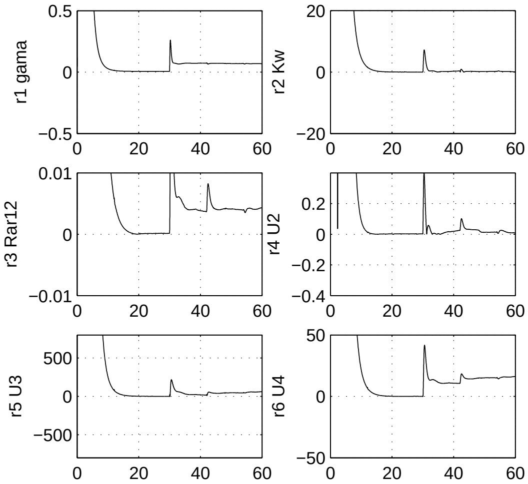

Fig. 6. Residuals for faults $gama$, R_{ar12} and u_4 at t=30 min.

As can be appreciated, the residuals r_1, r_3 and r_6 are actived for long time, i.e. the faults could be siolated with an adecuated evaluation strategy.

6. CONCLUSIONS

The paper presents an application of model-based approach to fault detection and isolation at the Fluid Catalytic Cracking Kellog Orthoflow F reactor/regenerator unit. Based on a linearised model of the FCC unit and assuming that the faults are constant, an augmented system for residual generation has been proposed. Results about fault detectability and isolability have been proposed. Three parameter changes (component faults) and three actuator faults were considered and the corresponding design of an observer-based residual to FDI has been carried out. The resulting residuals can detect the considered faults even if they are simultaneous. The schema has been tested using a non-linear simulation of the FCC unit. The proposed scheme allows to detect and isolate all the considered faults, even if they occur simultaneously. Note however, that all simulations has been realized for constant faults. The proposed approach allows the isolation of more faults that previous approaches with a reduced computational effort. The faults could be localized directly from the residuals in an easy way.

A further work will include the calculus of the residuals with real data, the comparison of different FDI strategies and the possible use of the results for the design of fault tolerant controllers.

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APPENDIX

State variables of the system:

T_{rx}=542.19640;	temp. of cracking mixture [°C]
H_{ra} =90.000010;	reactor catalyst holdup [ton]
C_{cat}=0.8913094;	catalytic coke [wt%]
C_{sc}=1.1288680;	carbon on spent catalyst [wt%]
T_{ra}=542.19650;	reactor bed temp. [°C]
H_{rg1}=305.19280;	reg. 1 stage holdup [ton]
C_{rc1}=0.3901241;	coke of the reg. 1 stage [°C]
T_{rg1}=670.14360;	temp. of dense phase 1 stage [°C]
O_{fg1}=0.2765286;	oxygen at 1 stage [mol%]
O_{d1}=0.2012453;	oxygen at 1 stage [mol%]
T_{d1}=681.91520;	temp. 1 stage dilute phase [°C]
H_{rg2}=64.338820;	reg. 2 stage holdup [ton]
C_{rc2}=0.2375586;	coke of the reg. 2 stage [°C]
T_{rg2}=700.88880;	temp. of dense phase 2 stage [°C]
O_{fg2}=0.2381298;	oxygen at reg. 2 stage [mol%]
O_{d2}=0.1508350;	oxygen at reg. 2 stage [mol%]
T_{d2}=704.38960;	temp. 1 stage dilute phase [°C]
O_{dg}=0.1171737;	oxygen conc. in flue gas [mol%]
T_{dg}=697.52540;	temp. of the dilute phase [°C]
P_{rg}=3.4524030;	reg. pressure [kgf/cm^2]
P_{circ}=3.4524030;	riser pressure [kgf/cm^2]
P_{ra}=2.8024030;	reactor pressure [kgf/cm^2]
P_{suc}=0.9999999;	suction pressure [kgf/cm^2man]
a_TCV=0.8200001;	TCV openning [0,1]
a_LCV=0.6281849;	LCV openning [0,1]
a_PdCV=0.72895;	PDCV openning [0,1]]