Simulation of Pressurizer for Steam Generator Tube Rupture of St. Prairie Island Nuclear Generating Plant, USA, using the MATLAB Environment

محبكبة الضبغط لمولذ بخبري عنذ حبدثت تمزق أنبوة بمحطت الطبقت النوويت بجزيرة سبنت بريري - بأمريكب ببستخذام بيئت MATLAB

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Abstract

The objective of this paper is to develop a simulator of a pressurizer component of a pressurized water reactor (PWR) power plant. The mathematical model of this simulator is developed from basic principle of physics, where mass and energy conservations were applied to a control volume. The pressurizer module is verified through simulation of St. Prairie Island Nuclear Generating Plant tube rupture accident. The boundary conditions required for the simulation of the pressurizer module were extracted from simulations of the accident using RELAP code. The module response predicted the trend of the pressure, quality, and water level in the pressurizer. The programing was performed under MATLAB environment. Analysis performed for the simulation of the pressurizer revealed an interesting linear relation between the derived coefficients of the model and the system state variables of the pressure or the quality. This suggests that improvement of the model in terms of speed of computation can be attained if such coefficient fitting to either of the state variables is performed.

Keywords: Steam Generator, PWR, St. Praire Island, MATLAB.

الملخص

الهدف من هذا الورقة محاكاة ضاغط لمحطة توليد الطاقة لمفاعل الماء المضغوط. تم إيجاد نموذج رياضي لهذا المحاكي من المبادئ الأساسية للفيزياء، وبناءً على المبادئ تم تطبيق قانوني حفظ الكتلة وحفظ الطاقة على حجم النظام. وللتحقق من صلاحية نمذجة الضاغط قمنا بمحاكاة حادث تمزق أنبوب مولد البخار في محطة جزيرة سانت باربارا، حيث استخدمت الشروط الحدودية من نتائج محاكاة الحادث باستخدام برنامج RELAP وذلك لتوظيفها في محاكاة نموذج الضاغط المعد في هذه الدراسة. كانت استجابة نموذج الضاغط متوافقة مع السلوك النمطي المتوقع للحادث لكل من الضغط والنوعية ومستوى ارتفاع الماء في الضاغط. نُفذت البرمجة تحت بيئة MATLAB حيث اظهر التحليل الذي أُجري لمحاكاة الضاغط علاقة خطية مثيرة للإهتمام بين المعاملات المشتقة من النموذج ومتغيرات الحالة المتمثلة في الضغط والنوعية وهذا يشير إلى أن تحسين النموذج من حيث سرعة الحساب يمكن تحقيقه إذا اُستبدلت معاملات النموذج الرياضي بالمعادلات الخطية المناسبة لكل معامل منها كدالة في الضغط أو النوعية.

Introduction

In the world more than 290 pressurizer water reactor (PWR) reactors representing about 64% of the world's nuclear reactors. These reactors use water for moderation and cooling, the coolant is not allowed to switch to steam inside the reactor core. Therefore, a secondary circuit is used to transfer the cooling water temperature and then to produce steam and generate electricity. The presence of the secondary circuit

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increases the safety of these reactors by separating the primary cooling cycle exposed to the radiation from the steam-generating cycle to the turbine. The pressurizer supplies and controls the system pressure in primary loop of PWR.

One of the main components of the PWR plants is the pressurizer, it is responsible to maintain and modify the station pressure. A steam generator tube rupture in a pressurized water reactor can lead to an atmospheric release bypassing the containment via the secondary system and exiting through the power operating relief valves of the affected steam generator. that is the main reason why steam generator tube rupture (SGTR) historically have been treated in a special way in the different deterministic safety analysis, focusing on the radioactive release more than in the possible core damage, as it is done in the other loss of coolant accidents [1].

Mathematical Model of a Pressurizer

In this section, a variable sized pressurizer mathematical model is derived based on physical principles. The derived model is then modified for affixed volume model of the pressurized simulator. Firstly, will use energy and mass balance on a control volume [2,3].

- **Mass and energy balance:**

Using some equations from thermodynamics:

Internal energy = enthalpy – work done

$$U = H - \frac{PV}{J}$$

$$m.u = m.h - \frac{PV}{J} \qquad (1)$$

$$\frac{\partial}{\partial t}[m.u] = M\frac{\partial h}{\partial t} + h\frac{\partial m}{\partial t} - \frac{1}{J}\left[P\frac{\partial V}{\partial t} + V\frac{\partial p}{\partial t}\right] \qquad (2)$$

1. **Mass Balance:**

Rate of mass change = Input of mass flow rate – output of mass flow rate

$$\frac{\partial m}{\partial t} = \sum_i Wi - \sum_j Wj \qquad (3)$$

2. **Energy Balance:**

Change rate of internal energy = rate of heat added to system + rate of enthalpy added due to mass flow rate exiting and entering of the system – energy equivalent of the work done by boundary [2,3].

$$\frac{\partial}{\partial t}[m.u] = Q + \sum_i Wi.hi - \sum_j Wj.hj - \frac{1}{J}P\frac{\partial V}{\partial t} \quad (4)$$

Substitute for $\frac{\partial}{\partial t}[m.u]$

$$\therefore m\frac{\partial h}{\partial t} = Q + \frac{V}{J}.\frac{\partial p}{\partial t} + \sum_i Wi(hi - h) - \sum_j Wj\,(hj - h) \quad (5)$$

Quality-pressure model from mass- enthalpy model

We develop mathematical model in terms of new state variables quality (x) and pressure (p). Knowing that specific volume and specific enthalpy are functions of quality and pressure [2,3].

$v = v(x, p)$ and $h = h(x, p)$ $\quad v = vf + x.(vg - vf) \quad h = hf + x.(hg - hf)$

And for pressure

$$\frac{\partial v}{\partial p} = \frac{\partial vf}{\partial p} + x.\left(\frac{\partial vg}{\partial p} - \frac{\partial vf}{\partial p}\right) \qquad \frac{\partial h}{\partial p} = \frac{\partial hf}{\partial p} + x.\left(\frac{\partial hg}{\partial p} - \frac{\partial hf}{\partial p}\right) \quad (6)$$

using the central difference interpolation technique to find $\frac{\partial v}{\partial p}, \frac{\partial h}{\partial p}$

$\frac{\partial m}{\partial t} = \sum_i Wi - \sum_j Wj$ Where; $m = \frac{V}{\upsilon}$ $\quad \frac{\partial}{\partial t}\left[\frac{V}{\upsilon}\right] = \frac{\upsilon\frac{\partial V}{\partial t} - V\frac{\partial v}{\partial t}}{\upsilon^2}$

$\frac{\partial V}{\partial t} = 0$ "Because volume is a constant"

$$\left[\frac{V}{v}\frac{\partial h}{\partial x}\right]\frac{\partial x}{\partial t} + \left[\frac{V}{v}\frac{\partial h}{\partial p}\right]\frac{\partial p}{\partial t} = Q + \frac{V}{J}.\frac{\partial p}{\partial t} + \sum_i Wi(hi - h) - \sum_j Wj\,(hj - h) \quad (7)$$

And is given in a matrix form as: AY=X

$$\begin{pmatrix} -\frac{V}{v^2}\frac{\partial v}{\partial x} & -\frac{V}{v^2}\frac{\partial v}{\partial p} \\ \frac{V}{v}\frac{\partial h}{\partial x} & \frac{V}{v}\frac{\partial h}{\partial p} - \frac{V}{J} \end{pmatrix}\begin{pmatrix} \frac{\partial x}{\partial t} \\ \frac{\partial p}{\partial t} \end{pmatrix} = \begin{pmatrix} \sum_i Wi \sum_j Wj \\ Q + \sum_i Wi(hi - h) - \sum_j Wj\,(hj - h) \end{pmatrix}$$

$$Y = A^{-1}X \quad (8)$$

From solution matrix we can get $\frac{\partial p}{\partial t}$ then, can present the following equation for the rate of change of quality as:

$$\frac{\partial x}{\partial t} = \sum_i BiWi + \sum_j BoWo + BQ$$

Where: $B = \left(\frac{v}{\Omega V}\right) * \left(\frac{\partial v}{\partial p}\right) \qquad Bi = \left(\frac{v}{\Omega V}\right) * \left[v\left(\frac{\partial h}{\partial p} - \frac{v}{J}\right) + \left(\frac{\partial v}{\partial p}\right)(hi - h)\right]$

$$Bo = -\left(\frac{v}{\Omega V}\right) * \left[v\left(\frac{\partial h}{\partial p} - \frac{v}{J}\right) + \left(\frac{\partial v}{\partial p}\right)(hj - h)\right]$$

Then, we can present the following equation for the rate of change of pressure is:

$$\frac{\partial p}{\partial t} = \sum_i A_i W_i + \sum_j A_o W_j + AQ$$

$$\frac{\partial p}{\partial t} = A_i W_i + (-A_i) W_{so} + A_o W_3 + AQ \quad (9)$$

Where: $A = -\left(\frac{v}{\Omega V}\right) * \left(\frac{\partial v}{\partial x}\right)$ $\quad Ai = -\left(\frac{v}{\Omega V}\right) * \left[\left(v\frac{\partial h}{\partial x} + \frac{\partial v}{\partial x}(hi - h)\right)\right]$

$Ao = \left(\frac{v}{\Omega V}\right) * \left[\left(v\frac{\partial h}{\partial x} + (ho - h)\frac{\partial v}{\partial x}\right)\right]$ $\quad \Omega = \left(\frac{\partial v}{\partial p}\frac{\partial h}{\partial x}\right) - \frac{\partial v}{\partial x}\left(\frac{\partial h}{\partial p} - \frac{v}{J}\right)$

Nuclear power plant St. Prairie island unit 1 steam generator tube ruptures accident

The event occurred on October 2, 1979 at Prairie Island Nuclear Generating Plant 530 MWe Westinghouse two-loop reactor. The failure occurred in the Steam Generator; the resultant leakage about 390 g/m. At the time of the accident, the plant was operating at 100% power [5]. At the moment the event occurred on 2 October at 14:14 High Radiation alarm on the air ejector discharge gaseous radiation monitor then, at 14:20 Over temperature turbine runback due to decreasing pressure (maximum rate was approximately 100 psi/minute.) .at 14:21 low pressurizer pressure (< 2139.9 psi) and commenced load reduction also low pressurizer level (< 18.3%) happened. at 14:23 started second and third charging pump. After 1m the reactor trip for "low pressurizer pressure" (< 1900 psi), minimum reactor cooling system (RCS) water inventory; RCS pressure begins increasing and safety injection occurred due to "low Pressurizer Pressure (<1815 psi). but at 14:26 reactor coolant pump 11 stopped. at
14:27 reactor coolant pump 12 stopped and at 14:30 emergency alert declared. at 14:32 11 steam generator level increased above the low level set point (13%) on the narrow range after having gone off scale low after the trip (It is normal for steam generator (SG) level to go off scale low on a trip; recovery in this case was much more rapid than usual). at 14:56 pressurizer level returned on scale and Stopped 12 safety injection (SI) pump. at 14:56:57 began depressurization of the RCS using the pressurizer power operated relief valve (PORV) (The valve was cycled 6 to 8 to reduce pressure times to required value). at 15:00 Site emergency declared after 2m pressurizer level reached the high-level set point (> 55%) and at 15:15 RCS pressure at 910 psi (same as 11 SG pressure) leak apparently stopped. at 15:50 commenced normal cooldown and at 2:00 site emergency terminated. 3 Oct at 06:40 residual heat removal (RHR) placed in service to continue cool down to cold shutdown finally 13:00 RCS at cold shutdown.
table (1) presents the Pressurizer's specification and its required boundary conditions.

The module, as it is standing alone, requires a set of boundary conditions to run its simulation. For the studied case of steam generator tube rupture accident, one needs the surge flow scenario, along with the activated controls on the pressurizer such as the relief valve flow rate during the accident.

Table (2) shows the relief valve flow history during the same period of simulation. It is noted that during the simulation, neither the spray nor the heater have been operated.

Also, table (3) represents the surge flow activated during the first 3000 second of the accident time.

Table (1) Specifications of the Pressurizer

Parameter	Specification (SI unit)	Specification (British units)
Height (length)	11.19 meter	36.72 Feet
Diameter	1.88 meter	6.1768 Feet
Internal volume	31.14 m^3	1100 Ft^3
Initial condition		
Pressure	15.5172 MPa	2250 psia
Quality	0.186622	0.186622
Conversion factor	5.405	5.405
Materials		
Inside clad	Austenitic stainless steel	
All internals	Austenitic stainless steel	
Upper/ lower heads and shell	Carbon steel	

Table (2) Relief valve data

Time (Sec)	Relief Valve Flow (Ibm/Sec)
0	0
2179	0
2180	1.75
2250	1.6
2600	1.25
2800	1.25
3000	1.1

Table (3) Surge flow data with time

Time (Sec)	Surge Flow (Ibm/Sec)	Time (Sec)	Surge Flow (Ibm/Sec)
0	-56	2160	0
95	-50	2180	-10
125	-5	2600	10
150	-60	2601	10
180	-40	2770	-18
240	53-	2771	-18
260	-395	2900	10
280	55	2910	-30
475	12.5	9292	-20
850	0	9292	4
1400	0	9292	4
1425	-5	5222	4
1500	3-		

Coding of the pressurizer module under MATLAB environment

Basically, in our programming we adapted the use of functions as our basic programming tool, integrated together under a main program to function appropriately. Figure (1) presents the coding functions used for the pressurizer module, followed by a brief description for each part of the chart. The general format for the function is given by:

Function [output] = interpolate (input)

This function uses the input given between the two curved brackets to calculate the values of the output presented between the two square brackets. The following is a description for the used functions:

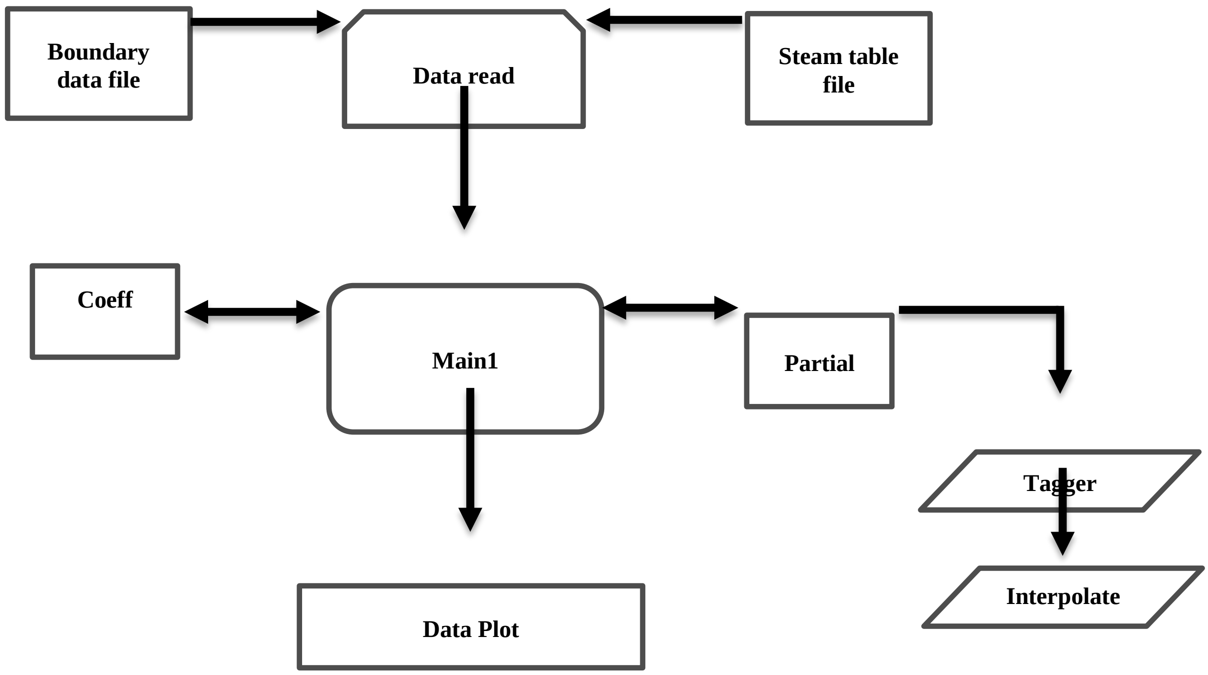

Figure (1) Coding the pressurizer module under MATLAB environment

Interpolate: `function Tstar=interpolate (pstar,itag,p,T)`

Boundary: `function [W1,W2,W3,Q,Wi, Wo,Wso,mm ]= Boundary(t,TIMERelif,RELIEflow, TIMEflow,SURGEFLOW)`

Coeff

(Confection's):`Function[Ai,Ao,A,Bi,Bo,B]=coeff(J,V,Hfstar,Hgstar,Afstar,v,h ,dvx ,dhx ,dvdp ,dhdp )`

Partial: `function [ Hfstar, Hgstar, Afstar, v ,h ,dvx ,dhx ,dvdp ,dhdp ] = partial( x ,pressure,p,T,Af,Ag,Hf,Hg )`

Calculates the saturated properties, as well as the partial derivatives (specific volume, enthalpy, $\frac{\partial v}{\partial x}, \frac{\partial h}{\partial x}, \frac{\partial v}{\partial p}, \frac{\partial h}{\partial p}$)

Data plot : `function dataplot()` Reads

and draws results from files.

Data read:

```
function
[p,T,Af,Ag,Hf,Hg,TIMERelif,RELIEflow,TIMEflow,SURGEFLOW]=dataread()
```

Reads of data from the steam table file, and the boundary conditions data files (('C:\hamida\data1.txt','r')/('C:\hamida\attempt2.txt','r')/ ('C:\hamida\attempt.txt','r'))

Tagger:

```
function itag=tagger(k,p,pstar)
```

The flow chart of simulation for the model of the pressurizer
This function brings the index for the pressure from table; if the pressure is found it provides its index, if not found it provides the indices for the pressure before and after.

Main1: `function`

```
main1()
```

Main1 is the basic program that uses all the provided functions to calculate the pressure, quality, and water level at any time t.

Results

Results of pressurizer response from steam generator tube rupture-accident is compared to our model response. figure (3,4) shows such comparison. The pressure in figure (3) shows pressure response during mitigation of tube rupture accident is load reduction, shutdown of the reactor (quickly scramming), pressure increase due to operation of emergency core cooling system (ECCS) in the reactor and the level off and the pressure decreased due to opening of pressurizer relief valves. but for the quality seen increase when the pressure decreases, the quality decrease when the pressure increases when operating emergency core cooling system (ECCS), the quality decrease when positive surge flow and the pressurizer quality decreased when operate relief valve. Also, the water level decrease when the pressure decreases (at accident), the water level will increase due to positive surge flow and the pressurizer water level decreases due to relief valves operation. Figure (5) shows pressurizer surge flow, total out flow, total in flow, relief valve, Spray valve, and Heater

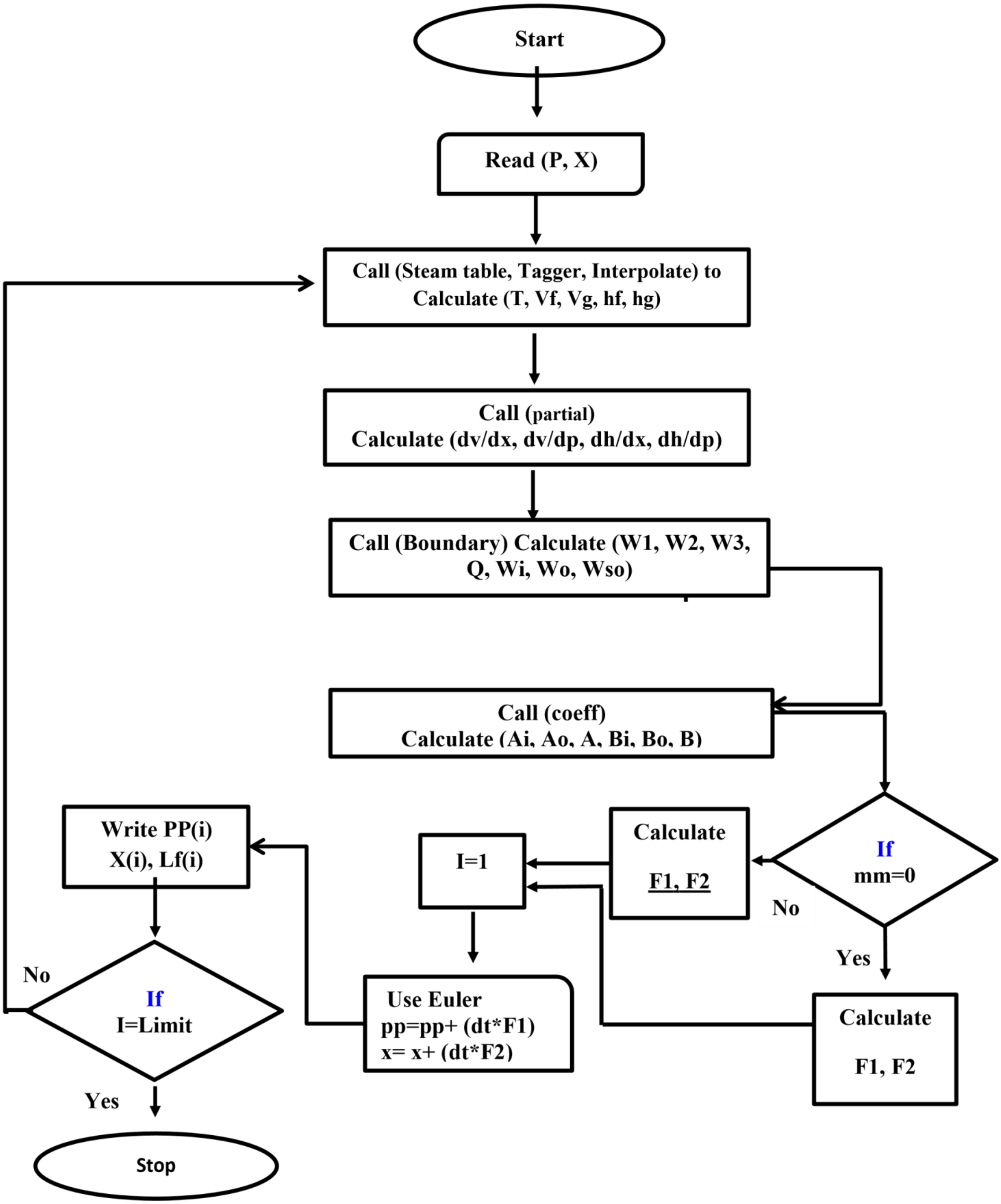

Figure (2) The flow chart for the calculations required during simulation

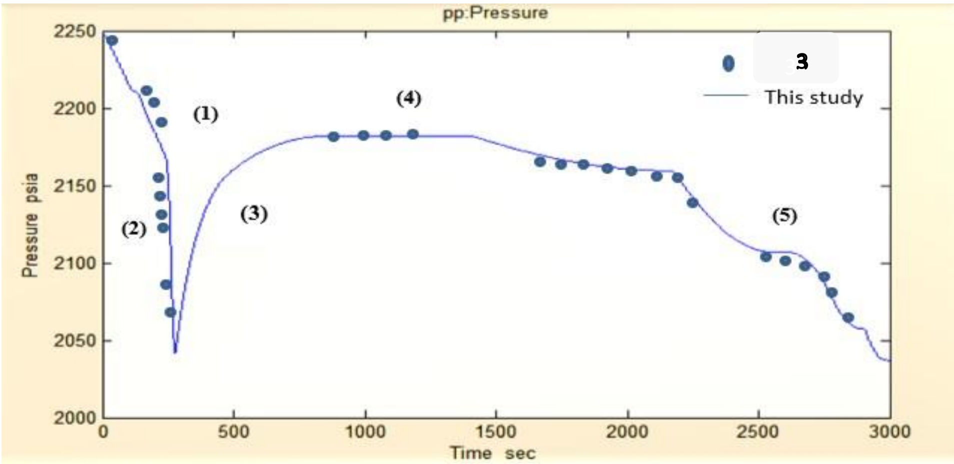

Figure (3) comparison between of pressurizer pressure response results from steam generator tube rupture-accident and our model response [3].

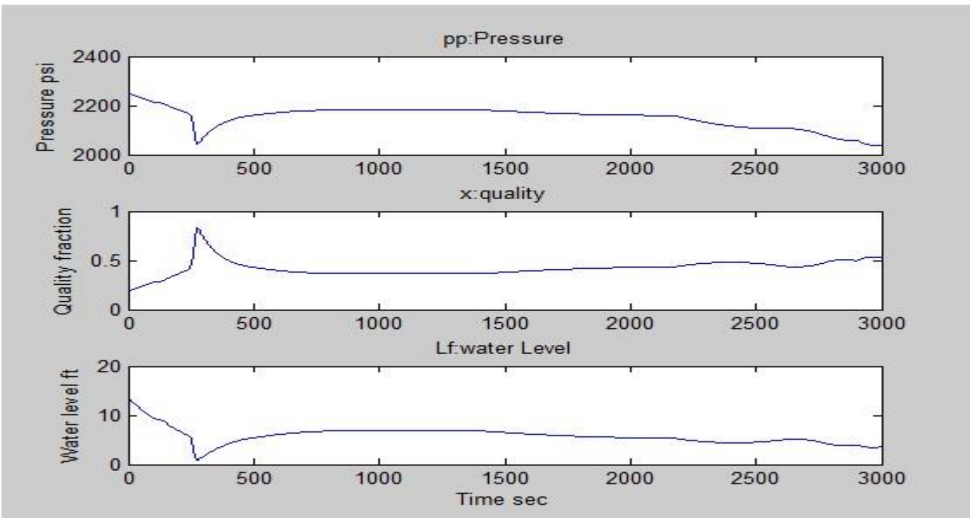

Figure (4) Pressurizer Water Level, Pressure, Quality Response

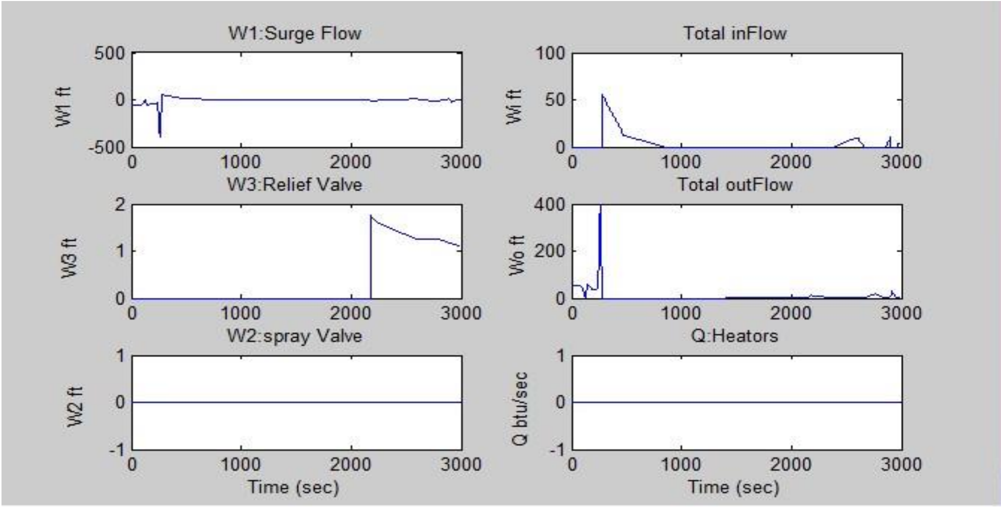

Figure (5) Pressurizer Surge flow, Total out flow, Total in flow, Relief valve, Spray valve, Heater Response

It is seen from Fig. (6) that the coefficients of the pressurizer model exhibit similar responses to either the quality state variable or the pressure state variable. Such resemblance suggests that one can correlate those coefficients to either of the pressure or quality variables. A linear relation of the form y= az + b, where y represents the coefficient A's or B's of the model, whereas z represents either the quality or the pressure variables, a, and b will be constants resulting from the related fitting. Such linear fittings can replace the A's and B's model coefficients which then speeds up calculations because one no longer needs to refer back to steam table data neither to calculate partial derivatives or make interpolations.

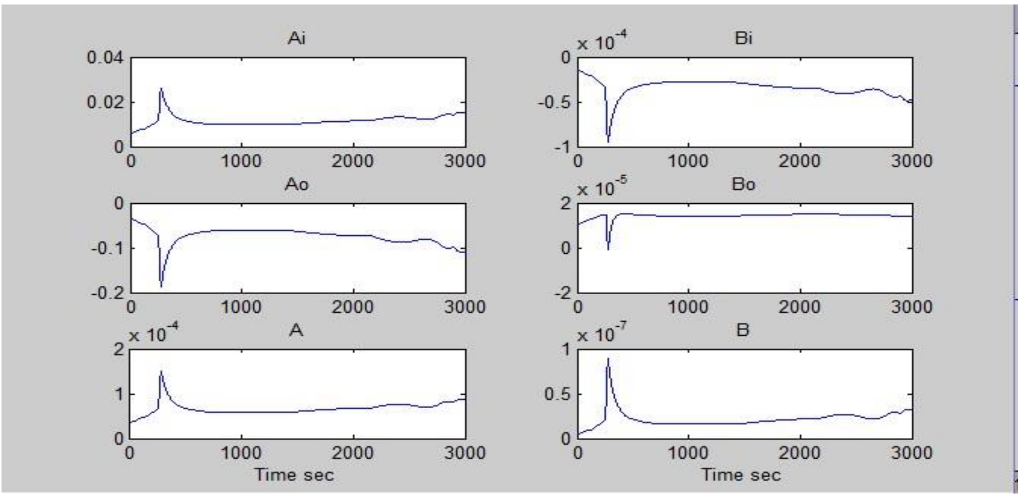

Figure (6) shows Pressurizer's A, Ai, Ao, B, Bi, Bo Response

Figure (7) shows Signature graph for Pressure and quality versus surge flow (W1) for SG_TR accident.

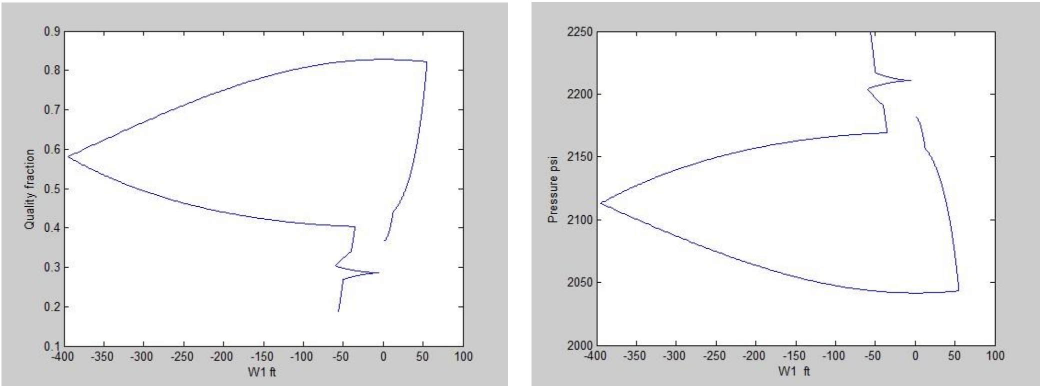

Figure (7) show Signature graph for Pressure, quality and surge flow (W1) for SG_TR accident

Conclusion

In this paper, a mathematical model derived from physical principles is presented. The model has been verified by simulating the pressure response and water level response for a steam generator tube rupture accident occurred in St. Prairie Island power plant in 1979. Boundary conditions to make the simulation of the accident has been used from RELAP code simulation studies of the same accident. The model generated similar trends of the accident in concern. The MATLAB environment has been used for programming was developed to work with the pressurizer module as a simulator. An interesting result from the post processor analysis revealed that the coefficients of the physical derived model can be correlated to either the pressure or quality to present them as a linear equation dependent on pressure or quality. Such new representation of the model will enhance the computation time.

Appendix

Scientific terms

Abbreviations H:

Total enthalpy h: Specific

enthalpy, $\frac{Btu}{1bm}$ U: Total internal

energy, Btu u: Specific internal

energy, $\frac{Btu}{1bm}$

V: Total volume, ft^3 υ f: Specific

volume of liquid, $\frac{ft^3}{1bm}$

J : Energy conversion factor Q: Heat transferred to the system, $\frac{Btu}{1bm}$ x: Quality of a two – phase mixture m: Mass inside the system, $1bm$ m_s: Mass of liquid inside system. m_g: Mass of steam inside system. m_{sg}: Mass of mixture inside system. Ap: Cross section area for the system, ft^2 L_f: Water level.

References

1. G. Jimenez, C. Queral, Rebollo-Mena, J.C. Martinez-Murillo, E. Lopez-Alonso, Analysis of the operator action and the single failure criteria in a SGTR sequence using best estimate assumptions with TRACE 5.0.
2. Wajdi Mohamed Ratemi and AH Musa Abo-Mustafa, General Model for PC-Based Simulation of PWR and BWR Plant Component,1994.
3. Wajdi Mohamed Ratemi, Hamida M. Shahat, A simulator of a pressurizer component with fuzzy logic control, decemper2018.
4. Peter Balint, Lisa Bladh, Apros simulation models for transient thermal hydraulic analyses of forsmark’s NPPs, 2008.