DYNAMIC SIMULATION OF BOILING WATER REACTOR STEAM DRUM

Mohamed Naguib Aly and S. Abou El-Seoud***

*Nuclear Engineering Department, Faculty of Engineering,
Alexandria University, Alexandria - Egypt.
** Reactor Department, Atomic Energy Authority, Cairo - Egypt.

ABSTRACT

A program, developed for digital personal computers, that simulates the dynamics of the inner region of a steam drum with saturated or superheated steam, leading to four possible steam / water states. By combining the linearized, small signal equations for each state, a non-linear model, about a reference condition, is developed. The equations are implemented using TUTSIM digital program. The thermal properties of steam and water are obtained over the pressure range of interest by simple approximations to steam tables.

Keywords: Steam Drum, BWR Dynamics, Energy and Mass Balance.

INTRODUCTION

A steam drum is a major component of a direct cycle boiling light water cooled (BWL) nuclear power plant. This describes the small signal (perturbation) simulation of the inner region of such steam drum. The data of the Gentilly LW-250 plant are used to generate a standard test case. For the steam drum under consideration, steam and water under saturation conditions enter the inner drum region from the separators. Steam leaves the drum to power the turbine, and water is fed back to the reactor via the inlet header.

BASIC ASSUMPTIONS

The basic assumptions used are:

1. No heat transfer occurs between the vessel materials and the fluids, nor between phases, other than by flashing or condensation. Figure 1 shows the simplified schematic diagram of the BWR steam drum, and the different flow rates used in the mathematical model analysis.
2. Steam can exist only in the saturated or superheated state, while water can exist only in the saturated or subcooled state. Neither supersaturated steam nor superheated water is permitted.
3. Instantaneous mixing occurs within each phase independently.

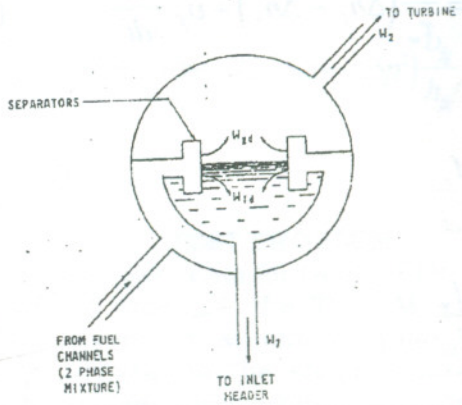

Figure 1 Simplified schematic of steam orum

CONSERVATION EQUATIONS

The steam drum for BWR nuclear power plants has been simulated by two regions and separated moving boundary in between. The basic equations are taken from References 1-3. They are derived for small changes about a reference (or steady state) condition. The nomenclature is given at the end of the paper. The symbol Δ means "a change in" while symbols without Δ imply reference conditions. The change in saturation enthalpies is given by subtracting Δh_s and Δh_w from Equations 1 and 2 respectively. Using these equations, the

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steam and water enthalpies have been obtained, in the case when the upper steam and the lower water are not saturated, these equations are given by :

$$\Delta h_g = \frac{dh_g}{dp}\Delta p \tag{1}$$

$$\Delta h_f = \frac{dh_f}{dp}\Delta p \tag{2}$$

$$\Delta h_g - \Delta h_s = \frac{dh_g}{dp}\Delta p - \Delta h_s \tag{3}$$

$$\Delta h_f - \Delta h_w = \frac{dh_f}{dp} - \Delta h_w \tag{4}$$

$$\frac{d\Delta h_s}{dt} = \frac{1}{\tau_s}\left(\Delta h_g - \Delta h_s\right) + \upsilon_g \frac{d\Delta p}{dt} \tag{5}$$

$$\frac{d\Delta h_w}{dt} = \frac{1}{\tau_w}\left(\Delta h_f - \Delta h_w\right) + \upsilon_f \frac{d\Delta p}{dt} \tag{6}$$

Where

$$\tau_s = \frac{M_s}{W_{gd}} \tag{7}$$

$$\tau_w = \frac{M_w}{W_{fd}} \tag{8}$$

The steam and water enthalpies, when saturated are given by :

$$\Delta h_s = \Delta h_g \tag{9}$$

$$\Delta h_w = \Delta h_f \tag{10}$$

As explained in Reference 1, saturation of water is equivalent to setting $\tau_s = 0$. In other words, Equations 5 and 6 are equivalent to Equations 9 and 10, respectively, if τ_s, τ_w equal zero. The pressure is given by:

$$D\frac{d\Delta p}{dt} = \upsilon_g\left(\Delta W_{gd} - \Delta W_2\right) + \upsilon_f\left(\Delta W_{fd} - \Delta W_7\right) + C_{ds}\left(\Delta h_g - \Delta h_s\right) + C_{dw}\left(\Delta h_f - \Delta h_w\right) \tag{11}$$

Where

$$C_{ds} = W_{gd}\left.\frac{\partial \upsilon_s}{\partial h_s}\right|_p \tag{12}$$

$$C_{dw} = W_{fd}\left.\frac{\partial \upsilon_w}{\partial h_w}\right|_p \approx W_{fd}\frac{d\upsilon_f}{dh_f} \tag{13}$$

The approximation in Equation 13 is very good due to the small compressibility of water. In Equation 11, D is one of the four constants, depending on whether the steam is saturated or superheated and whether the water is saturated or subcooled. This is illustrated in Table 1.

Table 1 VALUES OF D

Steam	Water	
	Saturated	Subcooled
Saturated	D_1+D_2	D_2-D_3
Superheat	D_1+D_4	D_4-D_3

The values of D_1 to D_4 are given by:

$$D_1 = f_1 M_w$$

$$D_2 = f_2 M_s$$

$$D_3 = \frac{d\upsilon_f}{dh_f}\upsilon_f M_w$$

$$D_4 = -\upsilon_g f_3 M_s$$

Where

$$f_1 = \left(\frac{dh_f}{dp} - \upsilon_f\right)\frac{\upsilon_{fg}}{h_{fg}} - \frac{d\upsilon_f}{dp}$$

$$f_2 = \left(\frac{dh_g}{dp} - \upsilon_g\right)\frac{\upsilon_{fg}}{h_{fg}} - \frac{d\upsilon_g}{dp}$$

$$f_3 = \frac{1}{\upsilon_s}\left.\frac{\partial \upsilon_s}{\partial p}\right|_h + \left.\frac{\partial \upsilon_s}{\partial h_s}\right|_p$$

In practice D_3 can be ignored, as it is negligibly small compared to D_1, D_2 and D_4. The rate of change of water mass in the drum is given by:

$$\frac{d\Delta M_w}{dt} = \Delta W_{fd} - \Delta W_7 + \Delta W_{con} - \Delta W_{f1} \qquad (14)$$

Where $\left| \Delta W_{con} = -C_{dg}\frac{d\Delta Mp}{dt} \right.$ If the steam is saturated

=0 if the steam is superheated

and $\Delta W_{f1} = -C_{df}\frac{d\Delta p}{dt}$

if the water is saturated

= 0 if the water is subcooled

Thus

$$\frac{d\Delta M_w}{dt} = \Delta W_{fd} - \Delta W_7 - C_{dg}\frac{d\Delta p^*}{dt} + C_{df}\frac{d\Delta p^*}{dt} \qquad (15)$$

Where the asterisk (*) indicates that the variable is switched in under the appropriate condition and where :

$$C_{dg} = \left(\upsilon_g - \frac{dh_g}{dp}\right)\frac{m_s}{h_{fg}}$$

$$C_{df} = \left(\frac{dh_f}{dp} - \upsilon_f\right)\frac{m_w}{h_{fg}}$$

Two conditions are necessary to maintain drum level, pressure and the mass of steam constant under steady state conditions, i.e.

$W_{gd} = W_2$
$W_{fd} = W_7$

STEAM AND WATER PROPERTIES

The following equations are approximations to saturated steam and saturated water properties over the range $3.5 \leq p \leq 7.5$ MN/m^2. The saturated steam properties equations and maximum errors are shown in brackets following each equation [1,6]:

h_g=2.79e6+ 8.98e-3 - 1.62e-9p^2 (0.1%)

h_f = 7.47e3 + 9.85e-2 p - 3.43e-9 p^2 (0.2%)

h_{fg} = 1.e9 / (476+2.68e-5 p) (0.2%)

v_g = 2.09e5/p - 2.46e-3 (0.4%)

v_f = 1.12e-3 + 3.3e-11 p (0.1%)

v_{fg} = 2.1e5/p - 3.97e-3 (0.5%)

$$\frac{dh_g}{dp} = (0.0196/p - 2.35e-9 - 1.26e-15p)h_{fg} \quad (0.3\%)$$

$$\frac{dh_g}{dp} = (0.0196/p - 2.35e-9 - 1.26e-15p)h_{fg} \quad (1.6\%)$$

f_1 = (0.0804/p+2.05e-8)v_{fg} (0.3%)

f_2 = (0.847/p+2.05e-8)v_{fg} (0.3%)

$$\frac{d\upsilon_g}{dh_f} = 2.69e-11 + 5.217e-17p \quad (0.4\%)$$

The following equations are approximations to superheated steam properties over the range $3.5 \leq p \leq 7.5$ MN/m^2 and up to 25 C of superheat.

$$\left.\frac{d\upsilon_{sf}}{dh_s}\right|_p = (2.32 - 1.06e-7p + 5.26e-15p^2)\frac{\upsilon_{fg}}{h_{fg}} \quad (1.0\%)$$

f_3 = -1/1.26 p (1.0%)

TEST PROBLEM

Using the data for Getilly BLW-250 as a standard case [3], the TUTSIM package is used to solve the system of Equations 1to 13 with addition to the steam saturated and superheated properties. To test this simulation, a pressure controller is required to prevent the pressure from drifting off. It is a low-gain, proportional-plus-integral controller designed to have a little effect on the transient results. The disturbing function ΔW_s is also entered in the simulation circuit.

To prevent the mass of water ΔM_w from drifting off its amplifier is temporarily short-circuited (via switch). The flow disturbance ΔM_s is resulting in the nearly sinsoidal disturbance of the net steam inflow (ΔM_{gd} - ΔM_2 . The results are shown in Figure 2. Three conditions occur during the cycle :

1. Saturated steam - saturated water
2. Superheated steam - subcooled water
3. Saturated steam - subcooled water

The third condition (saturated steam - subcooled water) exists for only a brief period because the steam and water time constants τ_s and τ_w are nearly equal. The fourth possible condition (superheated steam - saturated water) never occurs because $\tau_s < \tau_w$.

Figures 2-a to 2-c illustrate the response of BWR steam drum to the sinusiodal variation of net steam inflow. Figure 2-b shows the change in steam drum pressure, which is varying in the same trained as steam inflow. Figure 2-c shows the change in water mass, which decreases linearly for a certain period of time and remains constant to the period when the pressure starts to decrease again.

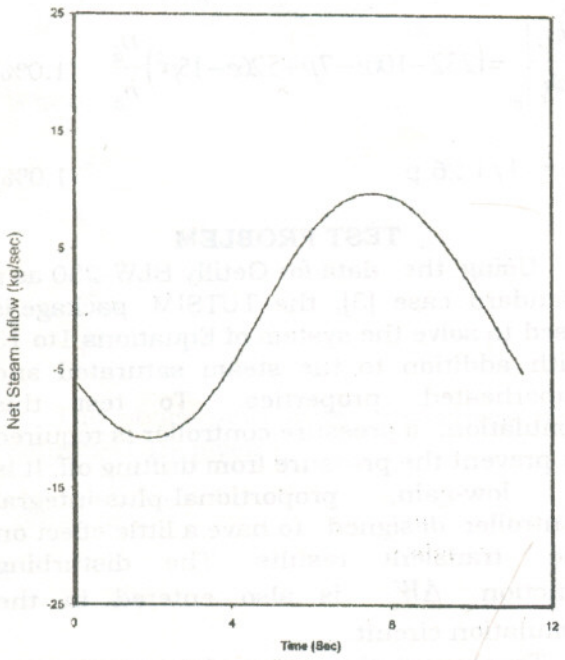

Figure 2-a The net steam inflow (kg/sec) versus the time (sec)

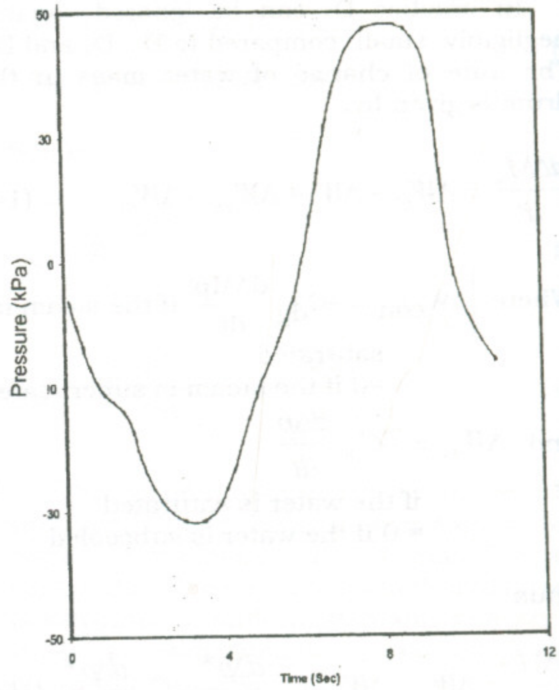

Figure 2-b The pressure (kP_a) versus the time (sec)

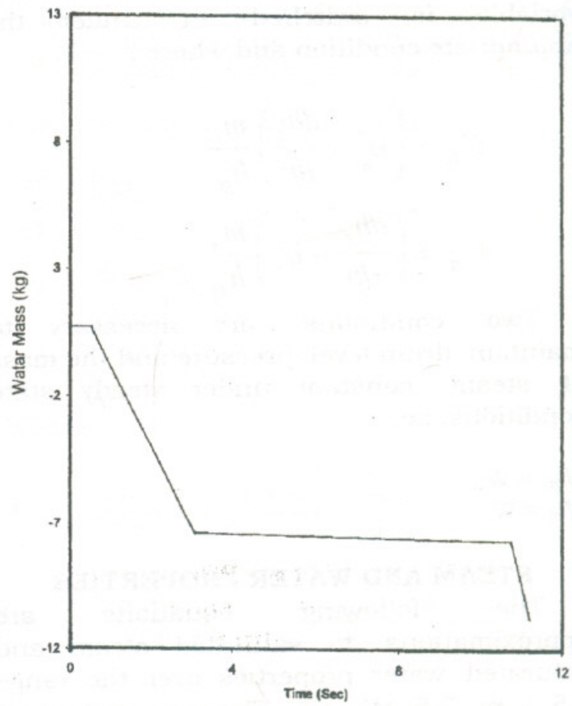

Figure 2-c Water mass (k_g) versus the time (sec)

CONCLUSIONS

In this paper, boiling water reactor steam drum model was investigated. In this model, various upper and lower conditions was tested. These conditions are saturated, subcooled water in the lower region. The main factor affecting the steam drum dynamics is the amount of steam in/outflow to the steam drum. The suggested model is suitable to cope with the overall boiling water reactor plant dynamics, in which the steam flow to the steam drum is directly affected by the overall plant transients.

NOMENCLATURE

c	Calculated coefficient which depends on drum properties
D	Denominator of equation and consisting of D_1 to D_4.
F	Calculated coefficient which depends on pressure only.
H_f	Saturated water enthalpy (J/kg)
h_{fg}	Enthalpy difference between steam and water
h_g	Saturated steam enthalpy (J/kg)
h_s	Steam enthalpy (J/kg)
h_w	Water enthalpy (J/kg)
K	Arbitrary constant
M_s	Mass of steam in drum (kg)
M_w	Mass of water in drum (kg)
p	Pressure, (N/m^2)
t_S	Mixing time constant of steam (sec)
t_W	Mixing time constant of water (sec)
v_f	Specific volume of saturated water (m^3/kg)
v_{fg}	Specific volume difference between saturated steam and water (m^3/kg)
v_g	Specific volume of saturated steam (m^3/kg)
v_s	Specific volume steam (m^3/Kg)
v_w	Specific volume of water (m^3/Kg)
W_2	Steam flow to turbine (Kg/s)
W_7	Water flow to inlet header (Kg/s)
W_{con}	Condensation rate (Kg/s)
W_{gd}	Steam flow into drum (Kg/s)
W_{fd}	Water flow into drum (Kg/s)
W_{fl}	Flashing rate (Kg/s)

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المحاكاه الديناميكية لاسطوانة البخار لمفاعل الماء المغلى

محمد نجيب على * و سمير شبل ابو السعود **

*قسم الهندسة النووية - جامعة الاسكندرية

**قسم المفاعلات - مركز البحوث النووية، الطاقة الذرية

ملخص البحث

فى هذا البحث تم تطوير ووصف برنامج عددى للحاسب الشخصى ليحاكى ديناميكيات المنطقة الداخلية لاسطوانة البخار بتواجد الماء اما المشبع او دون المبرد مع البخار اما المشبع او المحمص داخل اسطوانة البخار مما يؤدى الى اربعة حالات للماء مع البخار وقد تم تحويل مجموعة معادلات الحال الغير خطية الى معادلات حال خطية وقد تم تحويل حل هذه المعادلات باستخدام البرنامج العددى (TUTSIM) وقد تم الحصول على الخواص الحرارية للبخار والماء فى حدود مجال الضغط ذات الاهتمام باستخدام التقريبات البسيطة لجدول البخار