Modelling of Gas Mixed Saturated Steam Water Spaces using Coupled Single Equation Method

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Abstract **- Saturated Steam Water Spaces based equipment are employed in thermal and nuclear power plants. Single Equation Method based approach significantly improved the modelling of Saturated Steam Water Spaces, as it uses a mixed-phase analysis instead of conventional two phase multiple equation approach. The combined properties based single equation method, the Mass Factor-Volume Factor approach, further simplified the Single Equation methods and made modelling of Saturated Steam Water Spaces more efficient and computation friendly. When air or non-condensable gases are mixed into a saturated steam water space, the single equation method cannot be applied directly. Modelling of these spaces becomes relevant as most steam and water spaces contains small amount of non-condensable gases. These models are employed in the analysis of nuclear power plant containment, as steam or water at high temperatures leak into these spaces especially during accidents. A coupled steam water vapour space is proposed in this paper with the air space and the steam space coupled together as one model, still maintaining the single equation characteristics. The model was simulated using the combined properties approach and the simulation results are also discussed.**

Keywords - saturated Steam water spaces, SSWS, Coupled models, air-steam mixtures, MFact-VFact, Single Equation Methods

I. INTRODUCTION

Power utilities extensively employ operator training simulators to enhance operational efficiency of staff and this aids in optimal operation of plant and plant equipment [1]. The efficient and optimized use of plant and equipment help power utilities to generate power economically and reliably.

Fossil power plants (FPP) have numerous equipment using steam at saturation temperatures. The equipment include deaerators for removing air and non-condensable from steam, feed water heaters, boilers, condensers and steam turbines[2].Nuclear Power Plants (NPP), in addition to the saturated steam based equipment in FPPs, have many other equipment having saturated steam equipment including pressurizers, bleed condensers. Enclosed spaces having steam and water at saturation temperatures are termed as Saturated Steam Water Spaces or SSWS. Thus it is important to model SSWS for NPPs and FPPs for developing meaningful training simulators.

SSWS have water and steam at same temperature and are in equilibrium. In SSWS, the steam pressure is determined by the saturation temperature of the steam and have one to one relation. The Saturated Steam Tables provide a mapping of saturation temperatures with saturation pressures and vice-verse.

There were no generic modelling approaches for SSWS and SSWS equipment except for the modelling approach explained in [1]. These modelling approaches, though generic, use Two-Phase (steam and water), multiple equation approach in modelling the SSWS. Most of the modelling approaches tend to become model specific and these models rely on conversion of water to steam or steam to water due to heat added to or heat removed from the SSWS. Many SSWS models were based on this Conventional Internal Iterations Approach (CIIA), where the basic SSWS equations solved by iteration with intermediate temperatures. In CIIA, following a disturbance in an SSWS, for finding the new equilibrium temperature, an intermediate temperature is assumed. The basic equations are re-calculated at this intermediate temperature and based on the results, a new equilibrium temperature is assumed. This is followed till the approximation converges to a stable value of temperature [3, 1]. These internal iteration methods are neither computational friendly nor modeller friendly. CIIA models may not be able to handle large changes and therefore the changes are to be applied incrementally in steps. Large changes may prevent the sets of equations from converging. The earlier models used many redundant variables such as component mass and component volume of water/steam. These redundant component terms further complicated the modelling process of SSWS [3,5,9].

Many SSWS equipment models for control system were modelled using an approximated transfer function approach. Control Transfer Function based Pressurizer modelling approach was followed in [7]. Equipment specific modelling approach was followed in most SSWS equipment instead of using generic SSWS models. There are many models of pressurizer as an equipment with different modelling approaches [6,7].

To fill the vacuum of generic SSWS modelling, the Single Equation based SSWS models were proposed. Single Equation based generic SSWS model was based on the creation of a mathematical model with single equation describing the SSWS [3,5,9]. The single equation based SSWS modelling approach eliminated the need for internal iteration based methods.

The single equation methods also played a key role in eliminating the use of redundant component volume and mass of steam/water. With the single equation based methods as detailed in Section II, component volume and mass became optional in SSWS modelling. Thus Single equation methods has provided following advantages over conventional methods, especially CIIA [3,9,4].

- eliminating internal iterations,
- eliminating constituent Mass/volume
- eliminating all assumptions in SSWS models
- using mixed-phase approach instead of two phase multiple equation approach

SSWS models are dependent on Saturated Steam Tables for various properties of steam and water. The properties of steam and water are highly nonlinear. Computational models, derive the steam and water properties for the given temperature by

Interpolation [3,9,10]. Approximation functions may be derived for each of the properties of steam and water as a function of temperature. Accurate functions for finding out various steam and water properties at different temperatures is proposed in [10]. A polynomial approximation function of normalized temperature is proposed in [3,5,9]. These functions are not as accurate as approximation functions proposed in [10] but approximate functions can be obtained for the range of interest [3, 9].

Single Equation methods also can be used along with steam tables. The match can be obtained by steam table iteration and interpolation. If the steam and water propertied are replaced by approximation functions in the range of interest, SSWS equation can be re-modelled as a single equation as a function of temperature. A single equation as a function of temperature is proposed in [3, 9, 8] by combining the individual property equations. A comparison of computational speed of steam table iteration and that of polynomial function solution is reported in [9, 11]. The results depict that, considerable gain in terms of computational speed can be obtained by combining single equation method and polynomial approximation function. The polynomial function are at least 800% faster than the steam table iteration method [9, 11]. [4] Compares the computational speed advantage of CIIA method against SEM approach and the latter was around 1000 times (100,000%) faster than CIIA method.

The single equation based SSWS model can be restructured suitably by combining the steam and water properties to form a much simple equation. Mfact-Vfact Approach, the single equation based SSWS model with combined properties is proposed in [5]. The MFact-VFact approach reduces the number of terms in the single equation based model from ve to just three terms. The Mfact-Vfact approach proposes two combined properties MFact and VFact. With the MFact-VFact equation, the order of approximation equation could be reduced from 16 to 6[5]. Considerable reduction in number of terms and the order of the equation are achieved by employing Mfact-Vfact approach and this makes it one of the best suitable approach for modelling SSWS. Further Single Equation Methods supports in creating modular models of equipment and component as recommended in [1].

The single equation method enables the easy coupling of SSWS models with other models (SSWS or non-SSWS) to form tightly coupled models. These model coupling can be made through [12]:

- Mass: mass of water or steam
- Heat: external heaters, heat transfer
- Volume: volume of Steam or water.

In nuclear power plants, confinement of radioactive material is an important aspect; during normal operations, anticipated operational occurrences and other accident scenarios. In many nuclear reactor designs, third or fourth level of radioactivity confinement goal is achieved by means of strong structures enveloping the nuclear reactor known as Containment [13]. The strong containment structures are generally made from steel and concrete. The containment needs to be designed to withstand breaks in high energy systems including failures in steam system piping, steam generator leaks/ruptures and release of high enthalpy water or steam into containment atmosphere during Loss of Coolant Accident (LOCA) [14,13]. Therefore it is important to create mathematical model of the containment as Gas-SSWS, a mixture of steam with containment gases and subsequent containment pressurization and removal/addition of heat to containment atmosphere [13].

In Fukushima-Daichii, subsequent to a devastating earthquake & tsunami on March-2011, steam, air and hydrogen pressurized the nuclear reactor containment leading to containment failure and release of radioactive substances [15, 16]. Therefore containment mathematical modelling as a Gas-SSWS is important to nuclear power plant simulators for training operators.

II. THE SINGLE EQUATION BASED SSWS MODELLING

A. Basic Single Equation for SSWS

Simple example of an SSWS is a tank with steam and water. Let the volume, temperature and saturation pressure of the tank be *v, T, P*. The mass of water be m_s and that of steam be m_w. Similarly constituent volume of water and steam be v_w & v_s m^3 and density be d_w & d_s. Let the specic enthalpy of water and steam be h_w & h_s *KJ/kg* [3].

The total mass of water $m = m_s + m_w$ kg and that of $v = v_s + v_w$ m^3. Now $d_s = m_s / v_s$ and $d_w = m_w / v_w$.

Let H be the total heat or enthalpy KJ in the space/tank.

$$H = m_s h_s + m_w h_w \quad (1)$$

By rearranging and substituting constituent mass & volume, we get the Single equation based SSWS model [3, 9]:

$$m d_s h_s - v d_s d_w h_s + v d_s d_w h_w - m d_w h_w - H(d_s - d_w) = 0 \quad (2)$$

d_s, h_s , d_w , h_w are function of temperature and can be determined from the steam table. These properties have one to one relationship with saturation temperature and can be determined from the Saturated Steam Tables. Therefore 2 is a function of SSWS temperature T [3].

B. MFact-VFact Approach

The single equation based model 2 can be remodelled and recombined as as [5]:

$$H = m * M_{fact} - v * V_{fact} \quad (3)$$

where

$$M_{fact} = (d_s h_s - d_w h_w)/(d_s - d_w) \quad (4)$$

and

$$V_{fact} = d_s d_w (h_s + h_w)/(d_s - d_w) \quad (5)$$

Here, M_{fact}, V_{fact}, are based on steam/water properties only. Therefore all properties, d_s, h_s, d_w, h_w as well as M_{fact} and V_{fact} can be calculated from the SSWS temperature [5]. Approximation of properties as a function of temperature T is employed in [3, 9]. The following polynomial of degree l of temperature T may be used to describe an approximation function for a property $X = X(T, l)$ as:

$$X(T) = X(T, l) = a_0 + a_1 T + a_2 T^2 + . . . + a_l T^l$$

where $X(T, l)$ represents an l-th order polynomial with constants a_0 to a_l. d_w, d_s, h_s, h_w M_{fact} & V_{fact} can be expressed as a function of temperature T. Therefore 2 and 3 can be recognised as a function of SSWS temperature T. When properties are approximated as polynomials of temperature, 2 and 3 can be written as a polynomial function of temperature.

C. Modelling Gas Spaces

Gas only spaces may be modelled using Ideal Gas Equations. Consider a Gas Space with volume V L, Pressure P bar and temperature T ^OC. From Ideal Gas Equation:

$$P\ V = nR(T + 273:15) \quad (6)$$

where R= $0.8315 LbarK^{-1}mol^{-1}$ and n is the number of moles of the gas in the space.

n = mass-in-grams / molecular-weight

The energy in J of the gas in the space is given by:

$$H = (2/3)\ n\ R(T + 273.15) \quad (7)$$

For a Gas-Space, from 6 and 7, the pressure, volume of the space can be calculated.

III. MODELING GAS SPACE-SSWS

A. Gas Space SSWS Interaction

In Gas-SSWS interaction, it can be broadly divided into two types:

1. Non-condensable gas gets mixed in an SSWS. Here the major component is steam, generally encountered in SSWS including de-aerator of an FPP, bleed condenser or pressurizer of an NPP.
2. Steam enters an atmosphere of gas. This is generally encountered in NPP Containment, where steam ashes into the containment atmosphere during an accident.

An SSWS containing gas may be termed as Gas-SSWS or simply G-SSWS.

B. Conventional G-SSWS Modelling

G-SSWS can be analysed by CIIA method by adding the gas equations to the iterative SSWS equation list. The total energy is distributed between the constituents; air, steam and water. The partial pressures of steam and air are calculated. From the partial pressures, system pressure is calculated.

C. Coupling of SSWS Single Equations and Gas Equations

Consider a space where m_G kg of gas gets mixed with total mass of steam and water at m kg. Let the resultant temperature of the mixed space be $T^{O}C$. m_G *kg* of gas with molecular weight *molwt* may contain:

$n_G = m_G*1000/molwt$ moles.

Since the heat of both the systems are known, the two models can be coupled using heat.

Then the total heat *H* in the G-SSWS will be:

$H = H_G + H_{SSWS}$

and is given as a coupled equation by:

$$H = (2/3)n_G R(T + 273.15) + mM_{fact}(T) - v\, V_{fact}(T) \quad (8)$$

For example, if H_{Pr} is the heat in a previous cycle and H_a is added to the system, the new $H = H_{Pr} + H_a$. This equation can be solved for temperature *T* to find out the equilibrium temperature of the system for the new enthalpy H or any disturbance to the above equation. The Ideal Gas Equation part, $PV = nRT$ introduces one temperature based term into the general M_{Fact} -V_{Fact} equation. Equation 8 also takes care of the distribution of the heat into two components, one to SSWS (steam and water) and one to the gas in the space.

D. Estimating the System Pressure

In a space, the total pressure in the system will be the sum total of the partial pressure of the component gases. In this case there are two components, gas and steam. Pressure of steam or an SSWS is a function of its saturation temperature. Saturation pressure P_S can be obtained from the Temperature T ^{O}C using the steam tables or by employing suitable approximation function $PS = f(T)$. The partial pressure of gas P_G can be computed from 6. Therefore P_G in *Bar* is given by:

$$P_G = nR(T + 273.15)/1000\, v_S \quad (9)$$

Here gas volume V_g in L is the volume of the steam section v_s as the air is expanding only in steam space volume $v_s = v - v_w$.

The total pressure P_T of the system shall be:

$$P_T = P_G + P_S \quad (10)$$

Thus the total pressure of the space can be estimated from 9 & 10. In the case of steam mixed with air as discussed in Section-3.1, v_s can be considered as v itself as the mass and volume of condensed water m_W & v_W is negligible

E. Disturbances in Gas-SSWS

Equation (8) is the basic Gas-SSWS equation. From 8, the disturbances introduced to the system model are:

1. Change in *m*: change in mass of water or steam
2. Change in energy *H*: Heat added or removed from the system
3. Change in volume *v*
4. Mass of gas m_g introduced or removed from the system
5. Change in composition/molecular weight *molwt* due to association or disassociation of gases.

IV. EXPERIMENTS AND RESULTS OF SIMULATION OF GAS-SSWS

Simulation of Gas-SSWS equation is of prime importance, since most of the SSWS space has some dissolved gases in it. In cases of modelling containment, the pressure of the containment needs to be found out continuously to effectively simulate the containment and related system.

A. Simulation Experiments of SSWS mixed with Gas

Consider an SSWS with total mass *m* of steam and water at 3000*kg* and total volume *v* of steam (v_S) and water (v_W) be $12m^3$. Let the initial temperature of the SSWS be $180^{O}C$ and corresponding total heat *HSSWS* or *HT* calculated through 3 is 2378401.9*KJ*. The corresponding pressure of SSWS P_{SSWS} was approximated to be 10.109*Bar*. A sixth order polynomial was used to approximate V_{Fact} $(V_{Fact} = (T, 6))$ and a quadratic polynomial for M_{Fact} ($M_{Fact} = (T, 2)$). A fourth order polynomial (*T*, 4) was used for SSWS Temperature *T* to SSWS Pressure *P* mapping. Initially, the system was considered to be free of any gas (m_g = 0:0).

Air, with molecular weight 28.97gm/mol, at a temperature *Tg* of $100^{o}C$ was considered entering the SSWS at the rate of m'g 0.4*kg/S*. The SSWS and the air entrapped in the system was considered thoroughly mixed with the steam and assumed to reach the same temperature as of the SSWS. Therefore, the air or gas entering the SSWS will gain heat from or reject heat to steam to attain the equilibrium temperature *T*. The computational cycle time was considered at 1*S*. The MFact . VFact approach was used in the of Gas-SSWS coupled equation with polynomial approximation of $M_{Fact}(,T,\ 2)$ & $V_{Fact}(T,\ 6)$. Newton-Raphson method was used to find out the solution T of the polynomial equation. From T, SSWS pressure P_{SSWS} was determined. From the SSWS basic equations, steam volume v_S was determined and from volume v_S, partial pressure of gas was determined and subsequently the total pressure *PT* was determined.

B. Results and Analysis of Simulation of SSWS mixed with gas

The Table I shows the results of the simulation of Gas-SSWS model 3,7,8. mg represents the total mass of gas in the space, P_{SSWS} represents the pressure corresponding to Gas SSWS equilibrium temperature T. P_G represents the partial pressure exerted by the gas in the volume of steam v_S and P_T represents that of the total pressure of the Gas-SSWS.

TABLE I. SIMULATION RESULTS OF GAS-SSWS

Time (S)	m_g (kg)	H_T (KJ)	$T\ ^{O}C$	P_{SSWS} (Bar)	P_G (Bar)	P_T (Bar)
0	0.0	2378402	180.00	10.11	0.00	10.11
1.0	0.4	2379044	179.94	10.1	0.1	10.17
2.0	0.8	2379687	179.89	10.1	0.1	10.22
3.0	1.2	2380330	179.84	10.1	0.2	10.28
4.0	1.6	2380972	179.79	10.1	0.2	10.34
5.0	2.0	2381615	179.74	10.1	0.3	10.4
6.0	2.4	2382257	179.68	10.1	0.4	10.46
7.0	2.8	2382900	179.63	10.1	0.4	10.51
8.0	3.2	2383542	179.58	10.1	0.5	10.57
9.0	3.6	2384185	179.53	10.1	0.5	10.63
10.0	4.0	2384828	179.47	10.1	0.6	10.69
11.0	4.4	2385470	179.42	10.1	0.7	10.74
12.0	4.8	2386113	179.37	10.1	0.7	10.8
13.0	5.2	2386755	179.32	10.1	0.8	10.86
14.0	5.6	2387398	179.27	10.1	0.8	10.92
15.0	6.0	2388040	179.21	10.1	0.9	10.97
16.0	6.4	2388683	179.16	10.1	1.0	11.03
17.0	6.8	2389326	179.11	10.1	1.0	11.09
18.0	7.2	2389968	179.06	10.1	1.1	11.15
19.0	7.6	2390611	179.01	10.1	1.1	11.2
20.0	8.0	2391253	178.95	10.1	1.2	11.26

Simulation experiments were conducted for 20S and the total mass gas (air) mg entering the system was 8.0kg. SSWS and entrapped air are considered to be thoroughly mixed and at the same temperature. Since SSWS heat was shared with gas, the equilibrium temperature T of the Gas-SSWS dropped from 180OC (without any gas mixed) to 178.95OC (with 8.0kg of air), to increase the gas temperature (inlet 100OC) to equilibrium temperature T (~178OC). The total system pressure, PT steadily increased since the partial pressure of gas, PG was contributing in increasing the total pressure PT from 10.11Bar to 11.26Bar.

Figure 1 shows the change in computed pressures of SSWS (PSSWS), partial pressure of gas (PG) and the total pressure (PT) of the Gas-SSWS as a variation of mass of air (mg) in the SSWS. In the figure, the partial pressure of air is increasing as more quantity of air is added to the SSWS. The temperature of air entering the space is less that of the SSWS temperature. Therefore SSWS pressure is dropping slightly as the SSWS shares heat to the air to heat it the new equilibrium SSWS temperature.

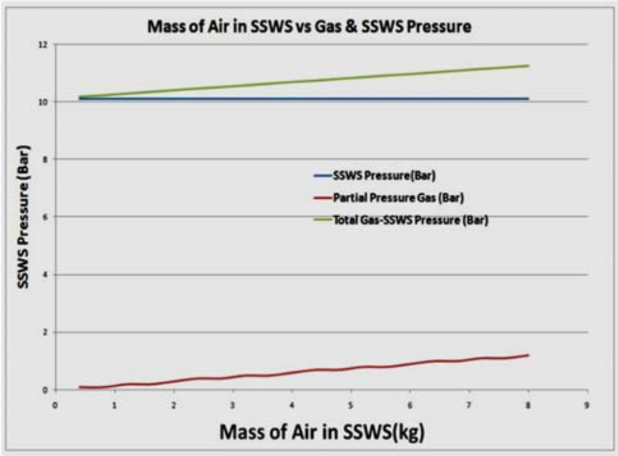

Figure 1. Gas-SSWS Pressure Vs mass of air in G-SSWS

V. CONCLUSION

Saturated Steam Water Spaces (SSWS) are widely used in the industry, especially in power plants. SSWS equipment have gases dissolved in steam or water and some equipment including deaerators, bleed condensers are used in removing air from the circuit. Nuclear Power Plant containment is another application where steam or saturated spaces interact with air or gases. In equipment where steam or very hot water interacts with air, analysis of gas mixed SSWS is needed. We have proposed an extension of the Single Equation based SSWS modelling technique for analysing and modelling gas mixed SSWS (Gas-SSWS). This coupled Gas-SSWS approach, carries the computational advantage of Single Equation method and modelling advantage of combined properties approach making the approach suitable for analysing and modelling Gas-SSWS. We have conducted simulation experiments to demonstrate the efficiency and applicability of Single Equation based coupled modelling approach in modelling Gas-SSWS. From the simulation approach, results and analysis, it is evident that the proposed approach is simple as well as efficient in Gas-SSWS modelling.

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