Modelling and Simulation of Coupled and Uncoupled Saturated Steam Water Spaces Using Single Equation Method

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***Abstract* — Simulators are extensively used as a tool for industrial training, design and development. Nuclear and Fossil Power Plants employ a number of equipments & systems operating in the saturation pressure/temperature region. There are no generic approaches available for modeling saturated steam water spaces. Methodology adopted in simulation & analysis of saturated steam & water spaces use multiple equations, complex algorithms and Steam-Tables and are specific to different equipment. When the computational models of saturated steam water space equipments & systems are interconnected or coupled with other models, the models become much more complex. These complex algorithms and steam tables adversily affect the speed of computation of these models. This paper for the first time proposes a generic quasi-steady state, quasi-numerical modeling approach using single equation methods instead of using multiple equations for modelling Saturated Steam Water Spaces. Using single equation method considerably reduces the complexity attached multiple equation methods. This paper focuses on the efficiency of the generic single equation based approach in coupling & combining saturated steam water space models with other models.**

Keyword - saturated steam water space; quasi-steady state modeling; coupled models; power plant simulation; performance optimization

I. INTRODUCTION

Most of the heavy industries use steam for heating purposes and as a power fluid. Fossil Power Plants (FPP) and Nuclear Power Plant (NPP) cycles use water & steam as their primary process fluid for the generation of heat and electricity. The feed water heaters, steam condensers, steam flash tanks, de-aerators, pressurizers, and bleed condensers (BCD) are some of the systems & equipments that are used in the industries and power plants [1], [2]. These equipments operate in the saturated temperature/ pressure region and can be termed as Saturated Steam Water Space (SSWS) systems. Most of the SSWS equipments & systems have other sub-components or sections which are coupled to the SSWS, directly or indirectly. Use of cooling coils, water spray systems, heaters in an SSWS based equipments are good examples of SSWS coupled to other systems/subsystems[1], [8], [9]. Modeling of these coupled systems & equipments require modeling of SSWS as well as coupling/combining the SSWS model with other non-SSWS or SSWS sub-system models.

SSWS models heavily depend on the saturated steam-tables (SST). The SSTs relate the properties of specific volume, density, specific enthalpy of steam & water at different temperatures[3]. Instead of using the SST based property values directly, property values generated by appropriate approximation functions also can be used. Least squares approximation based formulas for steam density, water density, specific steam enthalpy and specific liquid enthalpy are used in[4]. Simple non-linear functions for superheated and sub-cooled water properties in the range of 0.085 to 21.3MPa are used in [5]

International Atomic Energy Agency, IAEA, recommends the use of mathematical equations for estimating the thermodynamic properties of light water & heavy water including their vapor states. The equations are based on International Association for the Properties of Steam (IAPS) proposed IAPS-95 formulations. IAPS-95 formulations provide very accurate results but use very complicated equations based on fundamental Helmholtz Equations [6], [7]. To increase the computational speed for industrial applications, an industrial formulation IAPS-IF97 was developed using IAPS-95 formulations. [6].

Pressurizers are used in both Pressurised Water Reactors [PWR] and Pressurized Heavy Water Reactors [PHWR]. Pressurizer is an important component PWR and PHWR[8], [2],[1]. Pressurizers are generally modeled using the thermodynamic properties. Another method is to model pressurizer using transfer functions[8]. The pressurizer is modeled as a two-phase system with conservation equations considered in all phases in[9].

Modeling of SSWS using combined properties of steam & water is employed in[10]. This approach simplifies the modeling approach for SSWS considerably and reduces the overall turnaround time for SSWS modelers. Estimation of individual properties may still be required to derive the level of water or mass of steam in the SSWS[10]. Single equation based methods are very effective in improving computational speed of SSWS models. This improves the speed of computation by around 800% [11].

This paper proposes a numerical approach with polynomial approximation functions to replace the steam & water properties of SSWS. These polynomial approximation functions can be directly used in modeling of SSWS in quasi-steady state. Using one example, it is shown how the proposed modeling approach can be effectively used in modeling & simulation of SSWS models to other models by way of coupling.

The paper refreshes quasi-steady state approach and the basic equation used in SSWS from [11], [12] in Section-II. Final enthalpy equation of SSWS along with the approach to derive the approximation equations are explained in Section-III. Detailed modeling of SSWS in Quasi-Steady State is depicted in Section-IV. Application of approaches in coupled modeling is explained briefly in Section-V followed by the simulation studies carried out on proposed SSWS coupled models in Section-VI

II. Equations for SSWS Modeling

A. Quasi-Steady state modeling

Consider a tank total flow rate into a tank as m_{in} and flow rate out of the tank as m_{out}. Considering mass balance inside the tank for a computational time dt will be

Accumulation of mass = Inlet mass - outlet mass

Let previous mass in tank be m_{prev} & accumulated mass m_{acc}, then current mass in tank m_{tk} is given by

$$m_{tk} = m_{pr} + m_{acc} = m_{prev} + (m_{in} - m_{out})dt \quad (1)$$

During the time interval dt, the tank as in (1) is considered to have achieved steady state with no disturbance in the mass for the time dt. The tank is considered to have achieved quasi-steady state. This approach helps the simulation of large systems with individual model modules in quasi-steady state [12]. The main advantages of quasi-steady state approach are:

- A llows models to be more modular. Only tightly coupled equations are tied together into single module for computation.
- E ffective in responding to external events, including logical events. (In the example of the tank, failure of inlet/outlet valves can be effectively modeled in the valve model).
- N on-linearity of external components, non-linear inputs also can be handled with ease.
- A llows reconfiguration of components easily. Components can be added, deleted or modified easily.
- V ery effective in simulating large systems and plants.

B. SSWS Governing Equations

Consider an SSWS operating at the saturated pressure/temperature with steam and water in equilibrium state. Let mass in Kg of steam & water be denoted by m_s & m_w, specific enthalpy by h_s & h_w, , density by d_s & d_w, and volume of steam and water by v_s & v_w, . Let the total mass be m and the volume of the SSWS be v. Then total enthalpy (heat) H in the tank shall be

$$H = m_s h_s + m_w h_w \quad (2)$$

SSWS total mass m in kg is m= m_s+m_w and total volume $v=v_s+v_w$ Further $v_s=m/d_s$ and $v_w=m_s/d_w$.

In many approaches, an iterative method, with basic equations, is used to estimate the temperature or pressure of an SSWS. The properties are considered to be constant at a temperature T_0 and a new intermediate temperature T_1 is approximated. Using the properties at T_1, next intermediate temperature T_2 is reached. The iteration process is continued till the equilibrium temperature is reached. This may be termed as internal iteration[12].

Substituting and rearranging, we get after eliminating m_s, m_w, v_s, v_w

$$H(d_s - d_w) = md_s h_s - vd_s d_w h_s + vd_s d_w h_w - md_w h_w \quad (3)$$

$$md_s h_s - vd_s d_w h_s + vd_s d_w h_w - md_w h_w - H(d_s - d_w) = 0 \quad (4)$$

Equation (4) is the as single equation for modeling SSWS and does not contain terms related to individual mass/volume of water or steam, but only combined volume/mass of steam and water. This shows that an SSWS can be analyzed from its total mass, total volume, saturation temperature, energy added to the system. This equation eliminates the need of internal iteration based on intermediate temperatures [12].

The properties d_s, d_w, h_s, h_w are some functions of the saturation temperature T. The temperature at which (4) is satisfied shall give the saturation temperature. Here H, m, v are known quantities, h_s, d_s, d_w, h_w are drawn from SST as per the resultant saturation temperature of the SSWS [3]. Therefore in SSWS, for constant total enthalpy H, for a given v & m, the temperature and therefore pressure are constant. Therefore quasi-steady state analysis may be performed on SSWS without using any internal iteration [12].

III. Relation between properties and temperature/pressure

Steam table provides the steam/water properties at different temperatures. Each property has a different range. The relationship of properties d_s, h_s, , h_w as a variation of temperature in degree centigrade are shown in Fig-1. Here the actual values of properties and temperature are used. From Fig-1 it is evident that each property can be considered as a function of SWSS temperature though the relationship is complex[4],[3]. Since temperature and SSWS pressure bear a one-to-one correspondence, SSWS properties are also functions of SSWS pressure [12].

Rewriting(4), with d_s, h_s, d_w, h_w as functions of temperature t in ^{0}C / T in Kelvin we get

$$H = [md_s(T)h_s(T) - vd_s(T)d_w(T)h_s(T) + vd_s(T)d_w(T)h_w(T) - md_w(T)h_w(T)] \div [d_s(T) - d_w(T)] \quad (5)$$

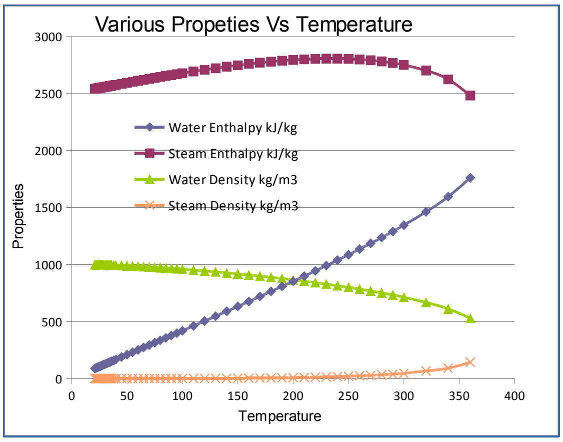

FIGURE 1: ACTUAL STEAM/WATER PROPERTIES VS TEMPERATURE[12]

A. *Deriving Approximation functions for Water Density*

An approximation function needs to be developed to analyze the behavior of water density d_w with respect to SSWS temperature T. Transforming temperature T to normalized form T_N (an N in the suffix denotes the variable is normalized). As T varies in 20 to 360^{0}C range, T_N, varies from 0 to 1 (Per Unit, PU) and is given by

$$T_N = (t - 20)/(360 - 20) \quad \text{in Centigrade unit}$$

TABLE 1: COMPARISON OF SIMULATED & ACTUAL ENTHALPY[12]

Temperature of Saturated Steam Space (0C)	Calculated Enthalpy (Approximated Properties) (KJ)	Enthalpy Actual (Using Steam Tables) (KJ)	Error (%)
100	540126.6	517307.8	-4.41106
120	655052.8	630958.4	-3.81871
140	769262.7	752122	-2.27897
160	886402.1	883291.2	-0.35219
180	1012347.5	1027068	1.433205
190	1080939.6	1104062	2.094327
200	1154668.6	1186537	2.685795
220	1321922.9	1363979	3.083345
240	1522685.9	1561155	2.464162
260	1764189.8	1788718	1.371287
280	2050393.8	2043409	-0.34182
300	2379245.6	2316521	-2.7077
320	2738739.0	2689596	-1.82714
360	3100953.6	3014646	-2.86294

$$T_N = (T - 293)/(633 - 293) \quad \text{in Kelvin unit}$$

T/t is thus expressed as t = A*T_N +B, where A is the Temperature Normalization range and B is the Temperature offset.

d_w decreases from 998 to 528.6 kg/m^3 as the temperature of SSWS increases from 20 to 360^{0}C. The normalized density of water d_{Nw} may be expressed as

$$d_{Nw} = (d_w - 998)/(528.6 - 998)$$

To find an approximate relation between normalized liquid density d_{Nw} & normalized temperature T_N, a 4th order polynomial of T_N was derived using least square approximation method. Thus d_w at saturation temperature can be expressed as a function of normalized temperature T_N where T_N = (T-B)/ A for Kelvin range

The normalized density of water d_{Nw} may be expressed as

$$d_{Nw}(T_N) = d_{Nw}(T_N,4) = 1.39612(T_N)^4 - 1.95123(T_N)^3 + 1.41663(T_N)^2 + 0.121467(T_N)^1$$

Here (T_N , m) = , where A_k are constants.

This approximation polynomial introduces a maximum error -1.51% at 360^{o}C. A simple approximation function $d_{Nw}(T_N)=(T_N)^2$ may be used with maximum error 5.22% at 320 ^{o}C. Use of lower order equations simplifies the analysis but introduces additional error. Fig-2 shows the comparison of fourth order polynomial & simple $(T_N)^2$ approximation of normalized water density with the SST based normalized water density for a normalized temperature of 20 to 360^{o}C. The fourth order polynomial approximation of T_N provides a fairly accurate representation of actual water density [12].

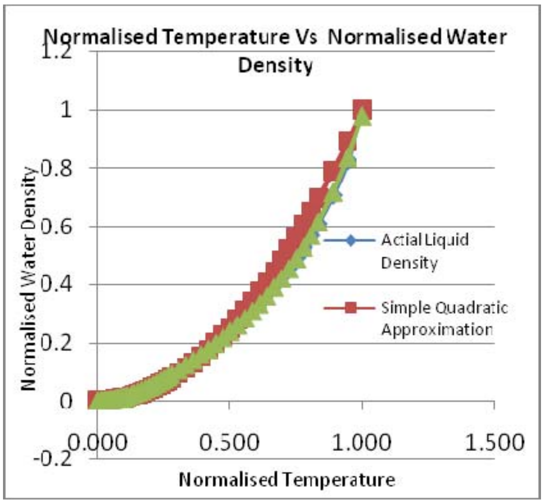

FIGURE 2: WATER DENSITY, POLYNOMIAL AND QUADRATIC FIT[12]

B. *Approximation functions for Simulation of Steam/Water Properties*

Similar to water density, specific enthalpy of water can be expressed as h_w = (P* $h_{Nw}(T_N)$ +Q) with maximum error of 0.75% at 360^{o}C where

$$h_{Nw}(T_N) = h_{Nw}(T_N,4) = 0.366(T_N)^4 - 0.332(T_N)^3 + 0.1197(T_N)^2 + 0.839(T_N)^1 \quad (6)$$

Similarly h_{Ns} can be expressed as and that of d_{Ns} as $d_{Ns}(T_N, 6)$.

Various assumption functions can be considered for each Steam/Water property as per the range of operation of SSWS to improve accuracy. Range of 100-360°C may cover HTS BCD transients but for a power plant steam condenser approximate functions for 10-100°C range may be suitable.

C. *Simulation of SSWS Enthalpy Using Approximated Equation*

Consider an SSWS with volume v=12m³ and mass of light water m=1200 kg. The Enthalpy H in kJ of the SSWS for the temperature from 100 - 360°C is calculated using (5). This considers that no mass is added/removed to/from the system during the cycle time dt and the system has attained saturation. This may be similar to HTS-BCD used in CANDU type NPPs to reduce the temperature of HTS heavy water at 300°C (10MPa) to 200°C (2MPa). HTS-BCD acts as a flash/expansion tank for the high temperature water and uses cooling & spray-system for effective heat removal[1], [2], [12]. This SSWS model considers light water as process fluid.

Fig-3 & Table-1 shows the SSWS total enthalpy values obtained using approximation functions and enthalpy values obtained from the steam table (SST) for temperatures in the range of 100 to 360°C. It is clear that the trend of calculated enthalpy using approximation functions and actual enthalpy computed with Steam-Table iteration-interpolation are similar with limited error. We used fourth order polynomial $(T_N, 4)$ for steam density for simplicity. Use of 6th order polynomial $(T_N, 6)$ may reduce error further. Temperature range used for the parameter approximation is 20°C to 360°C [12].

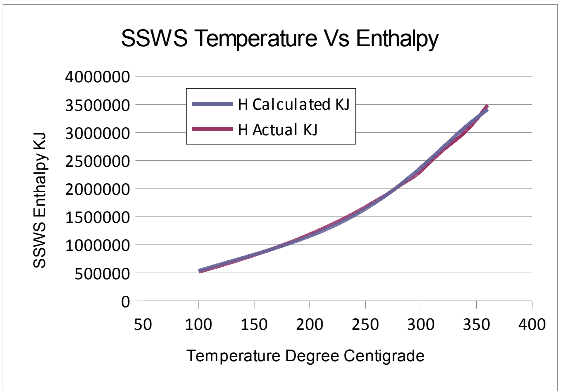

FIGURE 3: APPROXIMATE &ACTUAL HEAT VS TEMPERATURE [12]

IV. QUASI STEADY STATE MODELING OF SSWS

In SSWS modeling, analysis of relationship between enthalpy, mass, volume with Saturation temperature of the SSWS is essential[10]. Consider an SSWS as represented in Fig-4 with steam, water and heat input coming into or going out of the SSWS. Let the computational cycle time be dt. Heat can be directly added to the system using external heat sources or internal heaters. Let the total enthalpy (heat) addition rate may be H_{in} KJ/S. System may lose enthalpy (heat) directly to ambient or through cooling coils. Total enthalpy loss rate be H_{out} KJ/S. Total mass in the system be m kg. Liquid may enter the system through water inlets. Let this be m_{win} kg/S at temperature T_{win} °C and for steam inlet m_{sin} kg/S at temperature T_{sin} °C. Steam is extracted from the system at m_{sout} kg/S at previous system temperature T_{pr} °C. Similarly water is drained at m_{wout} kg/S at T_{pr} °C. Steam & water entering/leaving the SSWS is adding/removing heat as well as mass to/from the system. Let the existing SSWS mass be m_{pr}, volume be V_{pr} & enthalpy be H_{pr}. Therefore the current total enthalpy H in the system using conservation of energy equation is [12] :

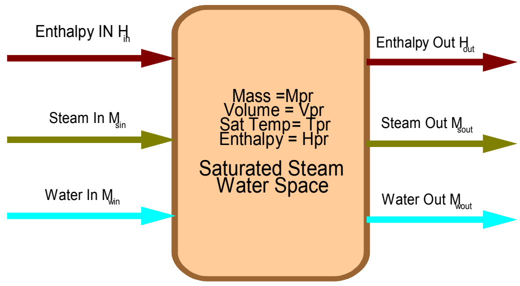

FIGURE 4: SSWS REPRESENTATION [12]

Current Enthalpy = Previous Enthalpy in system + Enthalpy added in dt time - Enthalpy removed in dt time

$$H = H_{pr} + (H_{in} + m_{win} * h_w(T_{Nwin}) + m_{sin} * h_s(T_{Nsin})) (H_{out} - m_{wout} * h_w(T_{Npr}) + m_{sout} * h_s(T_{Npr})) * dt \quad (7)$$

Previous enthalpy in SSWS can be computed (if not computed already) from m_{pr} and keeping $T=T_{pr}$

$$H_{pr} = [m_{pr} d_s(T) h_s(T) - m_{dw}(T) h_s(T) - v d_s(T) d_w(T) h_s(T) + m_{pr} d_w(T) h_s(T) + m_{pr} d_w(T) h_w(T)] / [d_s(T) - d_w(T)] \quad (8)$$

Current mass can be computed using the conservation of mass equation as

Current mass = Previous Mass in the system + Mass added in dt time - mass removed in dt time

$$m = m_{pr} + ((m_{win} + m_{sin}) - -(m_{wout} + m_{sout})) * dt \quad (9)$$

Now the current saturation temperature in the SSWS can be obtained by solving the equation for T_N using m, H as

$$[m * d_s(T_N) h_s(T_N) - v * d_s(T_N) d_w(T_N) h_s(T_N) +$$

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$$v*d_s(T_N)d_w(T_N)h_w(T_N)- m*d_w(T_N)h_w(T_N)] -[H*(d_s(T_N)-d_w(T_N))]=0 \quad (10)$$

The order of the approximation equation can be selected according to the range of operation of the SSWS or equipment. The solution can be obtained using numerical solution methods like Newton-Raphson method within the range of operation of the equipment/SSWS with T_{pr} as the starting temperature. Iteration using the properties obtained from the steam table and interpolation in the region of solution for the above equation may be needed in a conventional SST based approach[12].

V. Application of Proposed Approaches in Coupled Models

Consider an SSWS with a cooling coil with a fluid coolant flowing through the coil as represented in Fig-5. Let the temperature of coolant at the inlet of the cooling coil be T_{cin} and the corresponding normalized temperature be T_{Ncin}. The quantity of heat (enthalpy) transferred in dt time (rate of heat transfer at quasi steady state) to the SSWS is assumed a function of the temperature difference between temperature T of the SSWS and the T_{cin} [10] Assuming the heat/enthalpy transferred is linearly proportional to the difference in temperature, the enthalpy transferred H_{tr} to the system may be [12]

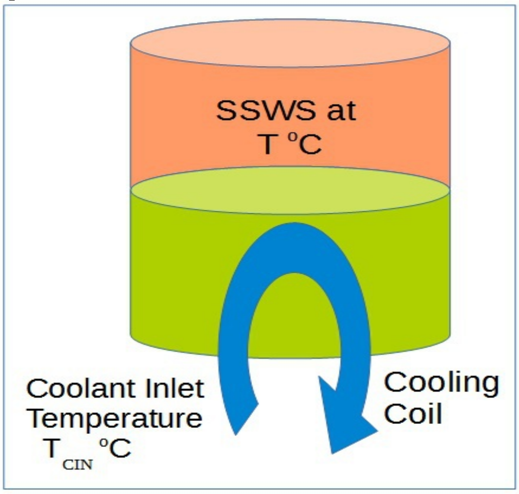

FIGURE 5: SSWS WITH COOLING COIL

$$H_{tr} = Constant*(T-T_{cin}) \quad (11)$$

$$H_{tr} = Constant* (A*T_N + B - A*T_{Ncin} - B) \quad (12)$$

$$H_{tr} = Constant*A*(T_N - T_{Ncin}) \quad (13)$$

$$H_{tr} = Q_{coeff}*A*(T_N - T_{Ncin}) \quad (14)$$

A is the temperature normalization range and B is the temperature offset. Q_{coeff} is the overall heat transfer coefficient/factor between the cooling coil & the SSWS, evaluated at steady state operating temperatures or by heat transfer calculations. Q_{coeff} is assumed to be constant across the operating region in this case. Let H_{tr} be the heat/enthalpy added in dt time. Now consider the energy balance equation in the SSWS.

Current Enthalpy = Previous Enthalpy in system + Enthalpy added in dt time - Enthalpy removed in dt time

$$H = H_{pr} - H_{tr}*dt \quad (15)$$

Applying (15) in (10) for new saturation temperature T_N

$$[md_s(T_N)h_s(T_N) - vd_s(T_N)d_w(T_N)h_s(T_N) + vd_s(T_N)d_w(T_N)h_w(T_N) - md_w(T_N)h_w(T_N)] - [H(d_s(T_N)-d_w(T_N))]=0 \quad (16)$$

In (16), only unknown factor is T_N and can be found out by solving the polynomial for T_N. T_N can also be found out using steam-tables.

This simple example of coupling of an SSWS model with a non-SSWS models shows that the quasi-steady state modeling approach can be efficiently used in coupling/combining SSWS and other models [12].

VI. Simulation of SSWS-Cooling Coil Coupled Model

Consider the coupled system with a cooling coil attached to it with mathematical model described by (14), (15) & (16) considering the simulation for only one cycle and dt as 1 Sec.

$$[md_s(T_N)h_s(T_N) - vd_s(T_N)d_w(T_N)h_s(T_N) + vd_s(T_N)d_w(T_N)h_w(T_N) - md_w(T_N)h_w(T_N)] - [(Hpr - Q_{coeff}A(T_N - T_{Ncin}))* (d_s(T_N)-d_w(T_N))]=0 \quad (17)$$

The combined single equation 17 was used for simulation SSWS-Cooling Coil for coupled models. The following general assumptions were made for conducting simulation experiments. Water of mass m 1000 kg at 290 ^{0}C is flashing into an empty SSWS of volume v of 12m^3. Therefore the total energy in the system H_{pr} is 1289000 KJ considering 1000Kg mass of water and enthalpy of water at 1289kJ/kg corresponding to 290^{0}C. Using Newton Raphson Method, without the cooling coil (uncoupled, with Q_{coeff} = 0 KJ/^{0}C) the temperature of the SSWS was calculated as 232.82^{0}C. Two sets of simulations were carried out in coupled model using 17, one by varying coolant inlet temperature T_{cin} (Refer Section-VI.B) and other by varying the Q_{coeff} (Refer Section-VI.A). Newton-Raphson Method was used in finding solution with the modified Single Equation based SSWS-Cooling Coil Coupled models. Temperature Normalization range adopted was 20 to 360^{0}C (A=340^{0}C)

A. *Simulation of SSWS-Cooling Coil Coupled Model by varying Q_{coeff}*

Table-2 depicts the variation of SSWS temperature obtained by changing the overall heat transfer coefficient Q_{coeff} between cooling coils and SSWS. In this simulation experiment SSWS total mass m, coolant inlet temperature T_{cin} were kept as constant. As the Q_{coeff} is increased, more heat is taken out by the cooling coil from SSWS and this reduces the SSWS resultant temperature. This effect can be clearly seen from the Fig-7

TABLE 2: SIMULATION OF COUPLED MODEL BY VARYING Q_{COEFF}

SSWS Total Mass m (kg)	Coolant Inlet Temperature T_{cin} (°C)	SSWS Temperature Without Cooling (°C)	Q_{coeff} (kJ/°C)	Coupled SSWS Temperature T (°C)
1000	40	232.82	500	222.64
1000	40	232.82	600	220.67
1000	40	232.82	700	218.71
1000	40	232.82	800	216.77
1000	40	232.82	900	214.85
1000	40	232.82	1000	212.95
1000	40	232.82	1100	211.08
1000	40	232.82	1200	209.22
1000	40	232.82	1300	207.39
1000	40	232.82	1400	205.58
1000	40	232.82	1500	203.79
1000	40	232.82	1600	202.02
1000	40	232.82	1700	200.28
1000	40	232.82	1800	198.56
1000	40	232.82	1900	196.86
1000	40	232.82	2000	195.18

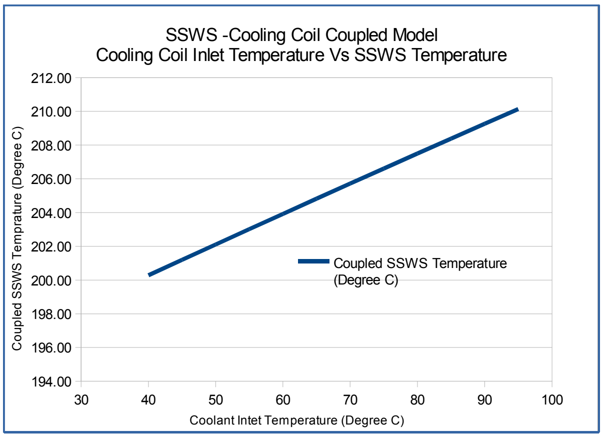

FIGURE 6: SIMULATION OF T_{CIN} VS SSWS TEMPERATURE

B. *Simulation of SSWS Cooling Coil Coupled Model by varying Coolant Coil fluid inlet temperature*

Table-3 pertains to the behavior of SSWS Temperature with respect to the variation in Cooling Coil inlet Temperature T_{cin}. As the Cooling Coil inlet temperature T_{cin} is increased, the heat transferred to the cooling coil reduces and SSWS temperature increases as shown in the Fig-5. Here the Q_{coeff} was selected as 1700 kJ/^{0}C arbitrarily.

TABLE 3: SIMULATION OF COUPLED MODEL BY VARYING T_{CIN}

SSWS Total Mass m (kg)	Coolant Inlet Temperature (T_{cin}) (°C)	SSWS Temperature Without Cooling (°C)	Q_{coeff} (kJ/°C)	Coupled SSWS Temperature T (°C)
1000	40	232.822	1700	200.28
1000	45	232.822	1700	201.19
1000	50	232.822	1700	202.11
1000	55	232.822	1700	203.02
1000	60	232.822	1700	203.92
1000	65	232.822	1700	204.82
1000	70	232.822	1700	205.72
1000	75	232.822	1700	206.61
1000	80	232.822	1700	207.50
1000	85	232.822	1700	208.38
1000	90	232.822	1700	209.26
1000	95	232.822	1700	210.14

C. *Conclusion*

The simulators of industries using steam as power fluid use many Saturated-Steam-Water-Space equipments and their simulation models. Most of the SSWS equipments combine of saturated steam water space and non saturated steam water space sections. This makes the coupling of these models essential for model efficiency and accuracy. We have proposed a generic quasi-steady state modeling approach using a single equation first time for SSWS only models. With the Single Equation method for SSWS, the use of intermediate steam or water mass and volume variables are not necessary. Being a quasi-steady state approach, internal cycling can be reduced considerably and being a quasi-numerical model, the modeling approach can reduce the dependency on steam-tables. We have described how the approach is very effective in coupling & combining SSWS with other models. Through simulation experiments carried out using the proposed model, we have demonstrated the effectiveness of the modeling approach when employed in simulation of coupled models. The proposed approach may help in redefining modeling of approach for complicated saturated Steam Water Space systems and equipments.

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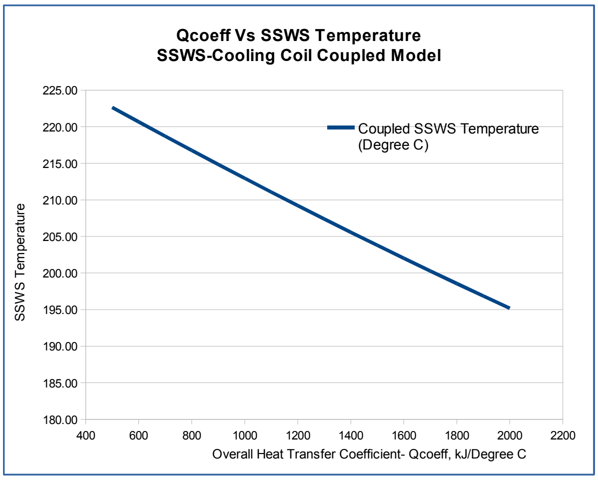

FIGURE 7: Q_{COEFF} VS SSWS TEMPERATURE

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