Experimental Investigation and Mathematical Modelling of Pressure Response for Steam Generator

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Abstract

Cold startup of boiler is the process of boiler operation with water at ambient temperature and pressure with all intake and discharge valves are fully closed to permit fast development of pressure. A mathematical model is developed to estimate the pressure response during cold startup of a perfectly insulated steam generator unit. A commercial type pressure switch is used in this unit to control and maintain the desired set point of the steam operating pressure. This mathematical model assume that the thermal properties of the supplied liquid water are temperature dependent. It is based on a novel Pressure Marching Technique that is coded using a FORTRAN language computer program. The maximum percentage error of (8.24 %) was obtained when comparing the predicted results of the mathematical model with the measured values obtained from the experimental test that was done using a (2 kW) electric steam generator unit with a volume of (30 litter) and maximum operating pressure of (8 bar). In addition, the same behavior of the predicted results was obtained when compared with results of a previously published article. It was found that the time constant of the pressure control system is directly proportional with its operating pressure set point and with the volume of the steam generator and its void fraction. A (50%) increase in the pressure set point will increase the time constant by (66.16%). Increasing the boiler volume by (166.667%) will increase the time constant by (166.677%) and increasing the boiler void fraction by (150%) will increase the time constant by (23.634%). The time constant is inversely proportional with the heating power of the steam generator. A (100%) increase in the heating power will decrease the time constant by (50%). The time constant is independent of the initial water temperature. Also, it was found that the time delay to start water evaporation is directly proportional with the volume of the steam generator. A (166.667%) increase in boiler volume will increase the time delay by (166.65%). The time delay is inversely proportional with the initial water temperature and with the heating power and void fraction of the steam generator. A (38.889%) increase in the initial water temperature will decrease the time delay by (8.882%). Increasing the heating power by (100%) will decrease the time delay by (50%) and increasing the boiler void fraction by (150%) will decrease the time delay by (16.665%). The time delay is independent on the operating pressure set point.

Keywords: pressure response; steam generator; boiler; Fortran; void fraction.

1. Introduction

Steam Generators or Boilers are devices that most commonly used in industrial, domestic applications and oil refineries. It uses Coal, Oil or natural Gas fuel or operated on electrical power to produce wet or superheated steam at a specific value of pressure and temperature. Wet steam dominates in most commercial and domestic applications; such as margarine and vegetable oils industry. On the other hand, Superheated steam contributes in many production lines including food, paper and drug industries, to mention just a few, in addition to its essential role in steam power plants, (AL-Saffar, 1994) and (Abdul Kareem and Rasheed, 2009).

The researches in boilers or steam generators dates many decades back attributed to its early contribution in industry. A theoretical study was conducted on a coal-fired steam generator as part of electrical power plant. The simulation program analyzed the dynamic response of the steam generator under step changes in steam demand. The results were compared with actual data from literature and it showed good agreement, (Terrence, 1973).

A nonlinear transient response, many lump, moving boundary dynamic model for a helical coiled once-through steam generator with non-uniform tube cross section was developed. The predicted results were verified with two other models and with an actual steam generator, (Ming-Huei and Lee, 1978).

Many researches focused on the control of water level in the boiler drums. A theoretical study to estimate the response of a heat recovery steam generator towards changes in drum water level was conducted. The model proposed a multivariable feedwater control design for the feedwater in connection with water level in drum. One of the design objectives was to minimize blowdown from the drums during start-ups. The results showed the improvement of the proposed design over the traditional single-loop feedwater control design, (Younkins and Chow, 1988).

A mathematical model for the dynamic analysis of a vertical reheat boiler and the application of this model to the optimal design of a drum water level controller was presented. A numerical Finite Difference Technique was developed to formulate this model. Results showed that an incremental PID controller plus adapt feedforward compensator can be successfully employed for the control of water level in boiler drums, (Zhao, 1992).

A mathematical modeling and simulation in MATLAB SIMULINK environment were developed to consider the possibility of steam production and supply process improvement

by perfection of the steam boiler control system, applying invariance principle that makes possible preemptive compensation of the influence of steam expenditure as a disturbance on the control process quality and efficiency. The control unit was low pressure steam boiler with one input impact to control – the heat flow of burning gas mixture fuel, one measured output parameter of the process – the steam pressure, and the main disturbance as a load impact – the steam expenditure. The mathematical and virtual models and block-diagrams for transient process simulation was compiled, allowing to start practical design and investigation of steam boiler invariant control system with high operation stability under essentially fluctuating load. The simulation results proved that the optimal solution for the transient process improvement in steam boiler, considering fluctuating load, was invariant PID-DPC two loop control system with disturbance impact on steam pressure preemptive compensation. Under invariant control the steam pressure overshoots decrease substantially in comparison with the traditional PID-feedback control method, (Sniders and Komass, 2012).

(Ponce, et. al., 2016) designed and evaluated a dynamic simulator for an ISCC (Integrated solar combined cycle) plant. The simulator is based on proportional-integral controllers and was developed in the MATLAB/Simulink® environment. A control strategy was presented. The intent of the strategy was to regulate the steam pressure of the superheater of the ISCC plant. The combined use of the simulator and the control strategy allows for the quantification of the reduction in fuel consumption that can be achieved when integrated solar collectors were used in a combined cycle plant. It was found that the ISCC plant simulator is suitable for designing, evaluating and testing control strategies and for planning the integration of solar and combined cycle plants.

(Chang, et. al., 2017) developed a mathematical model to analyze the transient response of the high-pressure steam pipeline network in a refinery. A sequentially iterative fully implicit method has been used to solve the unsteady nonlinear equations in a pipeline. The proposed method was then combined with the modified Hardy-Cross method to study the transient response in a looped pipeline network. A complex high-pressure steam network problem was used for demonstrating the applicability of the proposed solution method in analyzing the transient response in a pipeline network. This analysis was critical for optimizing operation and control of the steam distribution systems.

In this paper, a mathematical model will be developed to estimate the pressure response during cold startup of a perfectly insulated steam generator. A commercial type pressure switch will be used in this unit to control and maintain the desired set point of the steam operating pressure. This mathematical model assume that the thermal properties of the supplied liquid water are temperature dependent. It is based on a novel Pressure Marching Technique PMT that is coded using a FORTRAN language computer program. This technique is based on increasing the old value of boiler pressure to a new value by an increment, then estimating the incremental time that is required to heat the water by sensible heating and to evaporate a portion of water by latent heating. After storing the new updated values of time and pressure, the pressure and temperature of the water-vapor mixture is updated. The execution of the computer program is repeated in each new increment of pressure and it will be terminated when the new value of boiler pressure equals the pressure set point. The predicted results of the mathematical model will be compared with the measured values from the experimental test using a (2 kW) electric steam generator with a volume of (30 litter) and maximum operating pressure of (8 bar). Also, it will be compared with results of a previously published article.

2. Mathematical Model

Consider a perfectly insulated steam generator that is equipped with a pressure switch to control and maintain the desired steam output pressure value (P_o) during cold startup operation. At $(t = 0)$, the pressure set point on the pressure switch is suddenly changed to a unit step value of (P_{set}), and the water initial temperature inside the steam generator is (T_{W_i}), as shown in Fig. 1. It is required to predict the steam generator pressure response during cold startup operation.

To solve this problem, the following assumptions are considered:
1. The boiler is perfectly insulated.
2. The thermal properties of liquid water are temperature dependent.
3. The operating pressure range of the pressure switch is assumed within the range up to $(30 \ bar)$ as its availability in the local market.
4. Neglect the water level changes inside the boiler due to altering the input pressure signal.

2.1 Water Sensible Heating During

$(0 \leq t \leq t_D)$

At $(t = 0)$, the heater is activated by setting the desired value of boiler operating pressure to (P_{set}) in the dial of the pressure switch, the heater will release the heat to the water of mass (M) inside the boiler. This sensible heating of water will increase its initial temperature (T_{W_i}) to its new saturation temperature (T_{mix}^N) at its initial pressure (P_{atm}). Also, set the following values;

$$T_{mix}^{old} = T_{W_i}$$
$$P_o^{old} = P_{atm}$$

The time delay (t_D) to start water evaporation is estimated as follows;

$$\dot{Q}_H = \frac{\dot{Q}_{Sensible} + \dot{Q}_{Losses}}{t_D} \tag{1}$$

Since the boiler is perfectly insulated,

$$\dot{Q}_{Losses} = 0 \tag{2}$$

$$\dot{Q}_{Sensible} = M \ C_{P_w}\big|_{T_{mix}^{old}} \left(T_{mix}^N - T_{mix}^{old}\right)$$

$$t_D = \frac{\rho_w\big|_{T_{mix}^{old}} (1-\alpha) \ V_b \ C_{P_w}\big|_{T_{mix}^{old}} \left(T_{mix}^N - T_{mix}^{old}\right)}{\dot{Q}_H} \tag{3}$$

The values $\left(\rho_w\big|_{T_{mix}^{old}}\right)$, $\left(C_{P_w}\big|_{T_{mix}^{old}}\right)$ and $\left(T_{mix}^N = T_{mix}\big|_{P_{atm}}\right)$ are estimated as shown in table (1), (Rogers and Mayhew, 2004).

2.2 Pressure Marching Technique PMT

At $(t > t_D)$, water evaporation will start and the heater will continue to release the heat to the water-vapor mixture inside the boiler. This heat is divided into two modes. The first mode, is sensible heating of water to increase its temperature from its old temperature value (T_{mix}^{old}) to its new saturation temperature

value (T_{mix}^N). The second mode, is latent heating to evaporate a water of mass (m) at (T_{mix}^N). The PMT is based on increasing the old value of boiler pressure (P_o^{old}) to a new value (P_o^N) by an increment (ΔP), then estimating the incremental time (Δt) that is required to heat the water of mass (M), i.e. sensible heating, from its old temperature value $\left(T_{mix}^{old} = T_{mix}|_{P_o^{old}}\right)$ to its new saturation temperature value $\left(T_{mix}^N = T_{mix}|_{P_o^N}\right)$ and to evaporate a water of mass (m) at (T_{mix}^N), i.e. latent heating. The new value of time $(t^N = t^{old} + \Delta t)$ and the new value of steam output pressure $(P_o^N = P_o^{old} + \Delta P)$ is stored in a results file. A temperature update of the water-vapor mixture from its new value (T_{mix}^N) to its old value (T_{mix}^{old}) is needed. The execution of the computer program is repeated in each addition of a new increment value of (ΔP), and it will be terminated when the new value of boiler pressure $(P_o^N = P_{set})$.

$$Q_H^{\cdot} = \frac{Q_{Sensible}^{\cdot} + Q_{Latent}^{\cdot} + Q_{Losses}^{\cdot}}{\Delta t} \tag{4}$$

Since the boiler is perfectly insulated. Hence,

$$Q_{Losses}^{\cdot} = 0 \tag{5}$$

$$Q_{Sensible}^{\cdot} = M \, C_{P_w}\big|_{T_{mix}^{old}} \left(T_{mix}^N - T_{mix}^{old}\right) \tag{6}$$

$$M = \rho_w\big|_{T_{mix}^{old}} V_w$$
$$M = \rho_w\big|_{T_{mix}^{old}} (1-\alpha) V_b \tag{7}$$

$$Q_{Latent}^{\cdot} = m \, h_{fg}\big|_{T_{mix}^N} \tag{8}$$

$$m = \rho_v\big|_{T_{mix}^N} V_v = \frac{V_v}{v_g\big|_{T_{mix}^N}}$$

$$m = \frac{\alpha \, V_b}{v_g\big|_{T_{mix}^N}} \tag{9}$$

Substitute Eq. (5 to 9) into Eq. (4) and rearranging, yields;

$$\Delta t = \frac{V_b\left[\left\{\rho_w\big|_{T_{mix}^{old}}(1-\alpha)\right\} C_{P_w}\big|_{T_{mix}^{old}}\left(T_{mix}^N - T_{mix}^{old}\right) + \left\{\frac{\alpha}{v_g\big|_{T_{mix}^N}}\right\} h_{fg}\big|_{T_{mix}^N}\right]}{Q_H^{\cdot}} \tag{10}$$

Since the applicable operating pressure range of the commercial pressure switch is assumed within the range up to $(30 \; bar)$ as its availability in the local market. A segment of water and steam thermodynamic properties within this range is used, (Rogers and Mayhew, 2004). The best fitting model using CurveExpert Software version 1.34 to estimate each of the above thermal properties of liquid water and water-vapor mixture as shown in table (1).

To estimate the time constant (τ) of the steam generator, define the gain (G) of the steam pressure control system as follows, (Raven, 1995) and (Ogata, 2010);

$$G = 63\% \, P_{set} = P_o\big|_{(t-t_D)=\tau}$$

During the execution of the computer program, the time constant (τ) of the steam generator is approximately estimated if the following condition is satisfied:

$$If \quad |G - P_o^N| \le \varepsilon \quad \Rightarrow \quad \tau = t - t_D \tag{11}$$

Where $(\varepsilon = 1.0 \; Pascal)$.

3. Experimental Setup

A (2 kW) electric steam generator with a volume of (30 litter) and maximum operating pressure of (8 bar) is used during the experimental test as shown in Fig. 2-a. It is equipped with a commercial type pressure switch that is shown in Fig. 2-b, which is used in this pressure control system to control and maintain the desired output pressure (P_o) during cold startup. The initial water temperature is measured using a $(-10 \; to \; 200 \; ℃)$ thermometer and the output saturated steam pressure is measured using a $(0 \; to \; 6 \; bar)$ Bourdon gage. In addition, the time was recorded using a digital stop watch. Finally, the electric current and voltage that is operating the electric heater were measured using a DT266 clamp meter. Hence, the power of the electric heater is estimated as follows;

$$Q_H^{\cdot} = A \, . V \tag{12}$$

4. Calibration and Error Analysis

The BUDENBERG dead weight tester was used to calibrate the Bourdon gage and predict the percentage error for pressure measurements. Table (2) shows the results of the error analysis. It's clear that the maximum error of measuring pressure is (16.04%).

5. Results and Discussion

A mathematical model has been developed to estimate the pressure response during cold startup of a perfectly insulated steam generator. A commercial type pressure switch was used in this unit to control and maintain the desired set point of the steam operating pressure. This mathematical model is based on a novel Pressure Marching Technique that was coded using a FORTRAN language computer program that is shown in Fig. 3. It is assumed that the thermal properties of the supplied liquid water are temperature dependent.

5.1 Validation of Results

To validate the predicted results, an experimental test was done. Initially, at $(t = 0)$, the boiler of volume (30 litter) is (50%) filled with water, i.e. the void fraction of the boiler is set to $(\alpha = 0.5)$. The water temperature is $(18 \; ℃)$ and the pressure switch was set to $(P_{set} = 2 \; barg.)$. At $(t > 0)$, a list of measured values of the time, the output steam pressure (P_o), the electric current $(A = 8.85 \; Amp.)$ and voltage

$(V = 226\ Volt)$ were recorded respectively. When the output pressure (P_o) equals the pressure set point (P_{set}), the pressure switch will cut off the electric power to stop the heater. It was found that the maximum percentage error of (8.24 %) was obtained when comparing the predicted results of the mathematical model with the measured values obtained from the experimental test as shown in Fig. 4-a. The same behavior of the steam pressure response is illustrated in Fig. 4-b when a step-function change in (P_{set}) was applied after (40 sec.) approximately, (Ponce, et.al., 2016).

5.2 Pressure Response

Fig. 5 shows the change in steam generator pressure response when altering the rated power of the electrical heater. It is clear that increasing the rated power of the electric heater, it will reduce the time delay (t_D) to start water evaporation, Eq. (3), and it will reduce the incremental time (Δt) that is required to heat the water of mass (M), i.e. sensible heating, from its old temperature value (T_{mix}^{old}) to its new saturation temperature value (T_{mix}^{N}) and to evaporate a water of mass (m) at (T_{mix}^{N}), i.e. latent heating, Eq. (10). Hence, it will decrease the value of time constant of the pressure control system, Eq. (11), leading to a faster pressure response.

Fig. 6 shows the change in steam generator pressure response when altering the value of the void fraction of steam generator. It is clear that increasing the value of the void fraction of steam generator, it will reduce the time delay (t_D) to start water evaporation, Eq. (3), and it will decrease the incremental time (Δt) that is required to heat the water of mass (M), i.e. sensible heating, from its old temperature value (T_{mix}^{old}) to its new saturation temperature value (T_{mix}^{N}) and to evaporate a water of mass (m) at (T_{mix}^{N}), i.e. latent heating, Eq. (10). Hence, it will increase the value of time constant of the pressure control system, Eq. (11), leading to a slower pressure response.

Fig. 7 shows the change in steam generator pressure response when altering the value of the steam generator volume. It is clear that increasing the volume of steam generator, it will increase the time delay (t_D) to start water evaporation, Eq. (3). Hence, water evaporation will be delayed. Also, it will increase the incremental time (Δt) that is required to heat the water of mass (M), i.e. sensible heating, from its old temperature value (T_{mix}^{old}) to its new saturation temperature value (T_{mix}^{N}) and to evaporate a water of mass (m) at (T_{mix}^{N}), i.e. latent heating, Eq. (10). Hence, it will increase the value of time constant of the pressure control system, Eq. (11), leading to a slower pressure response.

Fig. 8 shows the change in steam generator pressure response when altering the values of input pressure set point. It is clear that increasing the value of input pressure set point, it will increase the value of output pressure and it will increase the saturation temperature of steam leading to a decrease in both values for latent heat of water evaporation and specific volume of dry saturated steam. Hence, it will increase the incremental time (Δt) that is required to evaporate a water of mass (m) at (T_{mix}^{N}), i.e. latent heating, Eq. (10). Hence, it will increase the value of time constant of the pressure control system, Eq. (11), leading to a slower pressure response. In addition, Fig. 8 shows

that the time delay (t_D) to start water evaporation is independent of the value of the input pressure set point.

Fig. 9 shows the change in steam generator pressure response when altering the values of initial water temperature. It is clear that increasing the value of initial water temperature, it will reduce the time delay (t_D) to start water evaporation, Eq. (3). Hence, it will decrease the value of time constant of the pressure control system, Eq. (11), leading to a faster pressure response. In addition, Fig. 9 shows that the time constant of this pressure control system is independent of the value of the initial water temperature.

6. Conclusions

The pressure response during cold startup of a perfectly insulated steam generator unit has been estimated using a mathematical model which is based on a novel Pressure Marching Technique that is coded using a FORTRAN language computer program. A commercial type pressure switch was used in this unit to control and maintain the desired set point of the steam operating pressure. This mathematical model assume that the thermal properties of the supplied liquid water are temperature dependent. In general, the following conclusions were found:

The time constant of the pressure control system is directly proportional with its operating pressure set point and with the volume of the steam generator and its void fraction. A (50%) increase in the pressure set point will increase the time constant by (66.16%). Increasing the boiler volume by (166.667%) will increase the time constant by (166.677%). Increasing the boiler void fraction by (150%) will increase the time constant by (23.634%).

The time constant of the pressure control system is inversely proportional with the heating power of the steam generator. A (100%) increase in the heating power will decrease the time constant by (50%).

The time constant of the pressure control system is independent of the initial water temperature.

The time delay to start water evaporation is directly proportional with the volume of the steam generator. A (166.667%) increase in boiler volume will increase the time delay by (166.65%).

The time delay to start water evaporation is inversely proportional with the initial water temperature and with the heating power and void fraction of the steam generator. A (38.889%) increase in the initial water temperature will decrease the time delay by (8.882%). Increasing the heating power by (100%) will decrease the time delay by (50%). Increasing the boiler void fraction by (150%) will decrease the time delay by (16.665%).

The time delay to start water evaporation is independent of the operating pressure set point.

Acknowledgements

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Nomenclature

$A =$ Electric current supplied to the electric heater, $(Ampere)$

C_{P_w} = Specific heat capacity of water, $\left(\dfrac{j}{kg.K}\right)$

h_{fg} = Specific latent heat of water evaporation, $\left(\dfrac{kj}{kg}\right)$

M = Initial mass of water, (kg)

m = Mass of saturated steam in the void of steam generator, (kg)

P = Pressure, $(bar\ abs.)$

P_{atm} = Atmospheric pressure, $(bar\ abs.)$

P_{set} = Input pressure, (set point value on pressure switch), $\left(\dfrac{N}{m^2}\right)$

P_o = Output pressure, (actual measured value of pressure), $\left(\dfrac{N}{m^2}\right)$

$\dot{Q}_{Latent}$ = Latent heat of water evaporation, (W)

$\dot{Q}_{Loss}$ = Heat losses to surrounding, (W)

$\dot{Q}_H$ = Power supplied by the electric heater, (W)

$\dot{Q}_{Sensible}$ = Sensible heat, (W)

T = temperature, $(°C)$

T_{W_i} = Initial water temperature, $(°C)$

t_D = Delay time, $(sec.)$

V_b = Volume of boiler, (m^3)

V_v = Volume of evaporated steam in the void of steam generator, (m^3)

V = Electric voltage supplied on the terminals of the electric heater, $(volt)$

Subscripts

mix = mixture

Superscripts

old = old

N = New

Greek Symbols

$\alpha =$ void fraction of the steam generator.

Δ = Increment.

τ = Time constant of the pressure control system, (sec.)

$\rho_v =$ Dry saturated steam density, $\left(\dfrac{kg}{m^3}\right)$

$\rho_w =$ Density of water, $\left(\dfrac{kg}{m^3}\right)$

$v_g =$ Specific volume of dry saturated steam, $\left(\dfrac{m^3}{kg}\right)$

Table 1: Best fitting model using CurveExpert Software version 1.34 to estimate the thermal properties of liquid water and water-vapor mixture, (Rogers and Mayhew, 2004).

Relation	Application Range	Best Fitting Model
$\rho_w\big|_{T_{mix}^{old}} = 1002.0946 - 0.16295195\left(T_{mix}^{old}\right) - 0.0026517445\left(T_{mix}^{old}\right)^2$	$(10 - 240\ C^o)$	Quadratic fit
$C_{P_w}\big|_{T_{mix}^{old}} = 4223.1643 - 1.795282\left(T_{mix}^{old}\right) + 0.016629066\left(T_{mix}^{old}\right)^2$		
$T_{mix}^N\big|_{P_o^N} = 72.66955 + 31.06599(P_o^N) - 3.6317573(P_o^N)^2$	$(1 - 30\ bar\ abs.)$	
$h_{fg}\big|_{T_{mix}^N} = 2491600.3 - 1847.6865(T_{mix}^N) - 4.6544423(T_{mix}^N)^2$	$(10 - 240\ C^o)$	
$v_g\big|_{T_{mix}^N} = [0.47190809 + 0.004640742(T_{mix}^N)]^{(-1/0.14083167)}$		Bleasdale Model

Table 2: Calibration and error analysis of Bourdon gage

Actual pressure (bar)	Pressure readings, (bar)			Correction (bar)			Error (%)
	Weight increase	Weight decrease	Average	Weight increase	Weight decrease	Average	
1.18	1.6	1.1	1.35	-0.42	0.08	-0.17	14.4
1.68	1.8	1.3	1.55	-0.12	0.38	0.13	7.73
2.18	2.2	1.7	1.95	-0.02	0.48	0.23	10.5
2.68	2.6	1.9	2.25	0.08	0.78	0.43	16.04
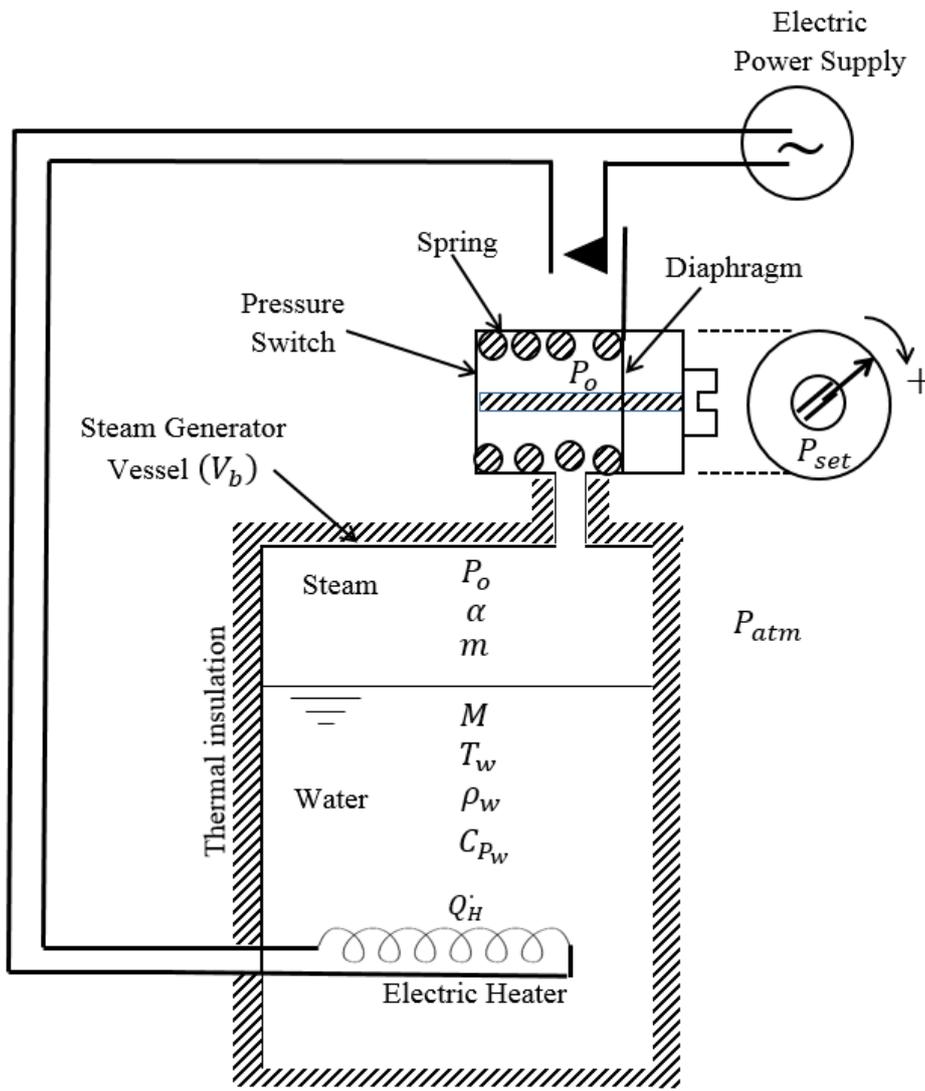
Fig. 1: Mathematical model
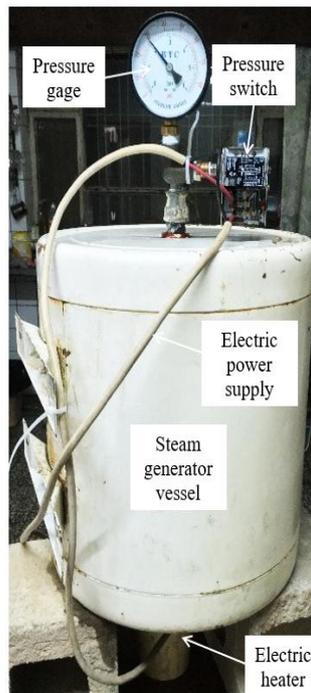
(a)   Photo
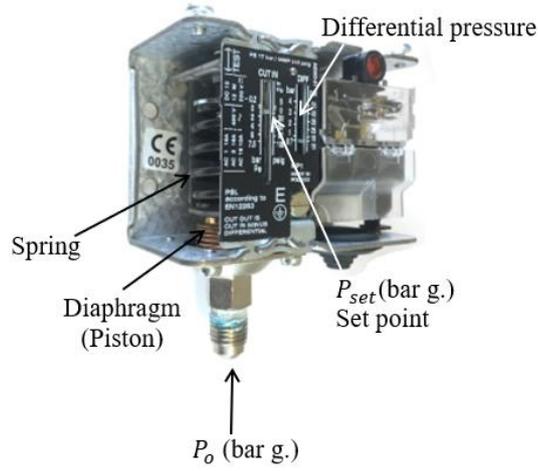
(b) Pressure switch
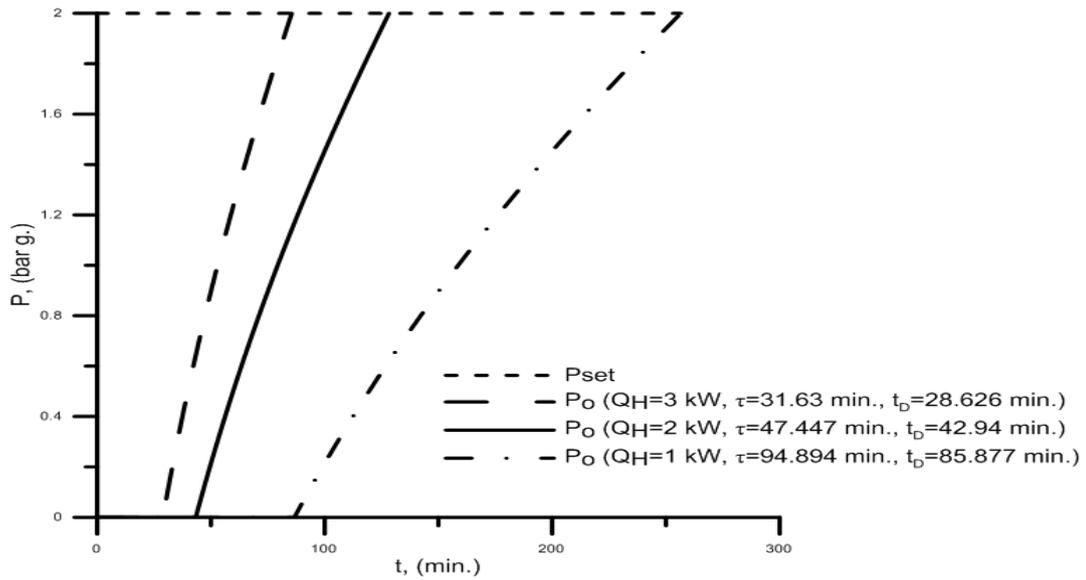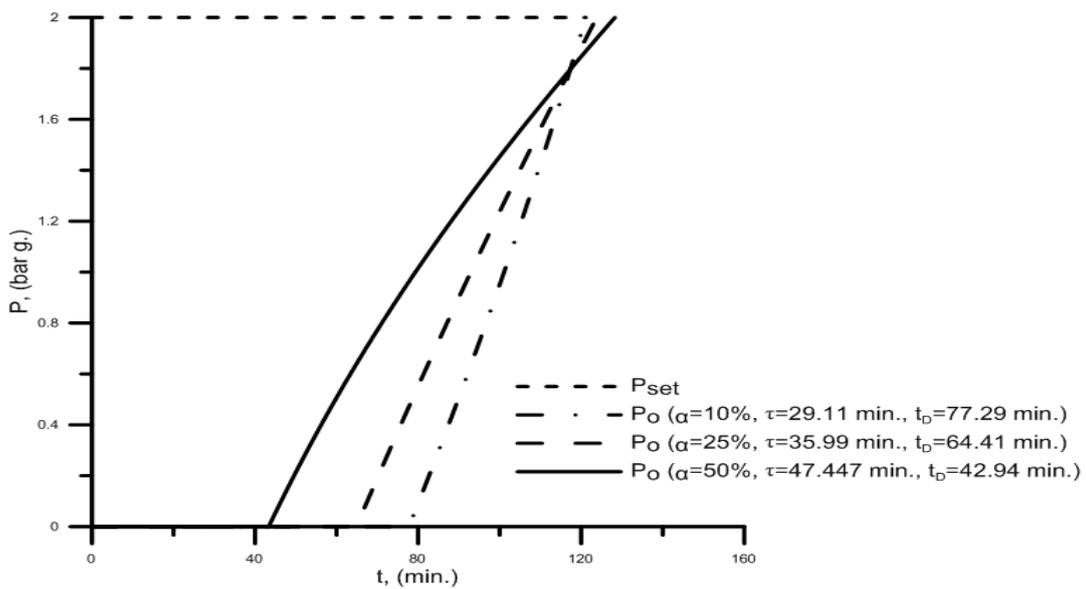**Fig. 2:** Test rig

Fig. 3: Computer program

(a)　　　Present work
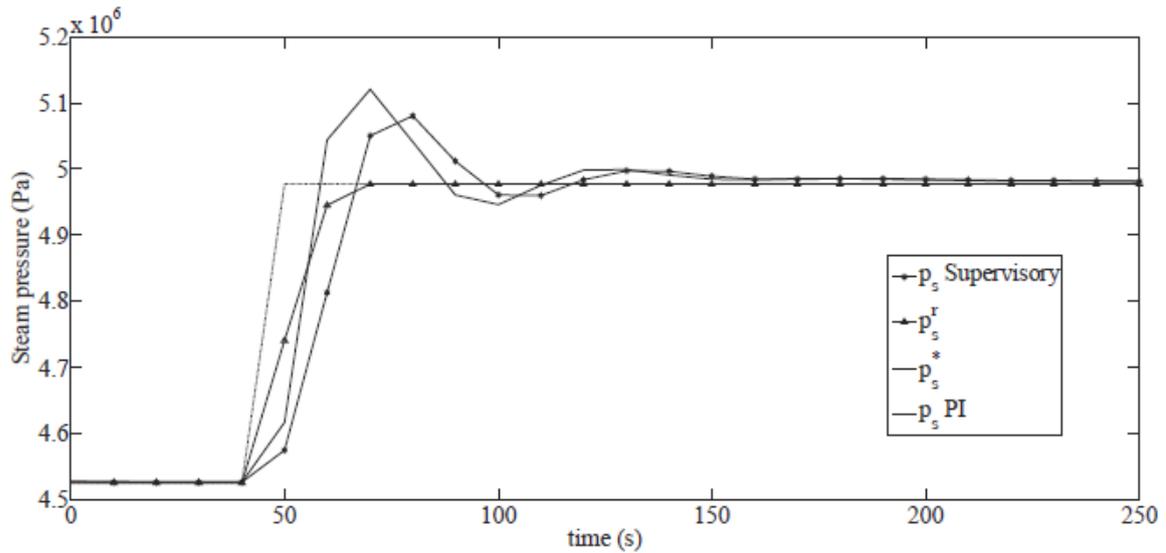
(b) (Ponce, et.al., 2016)
Fig. 4: Validation of results

Fig. 5: Steam generator pressure response for different values of rated power of electric heater

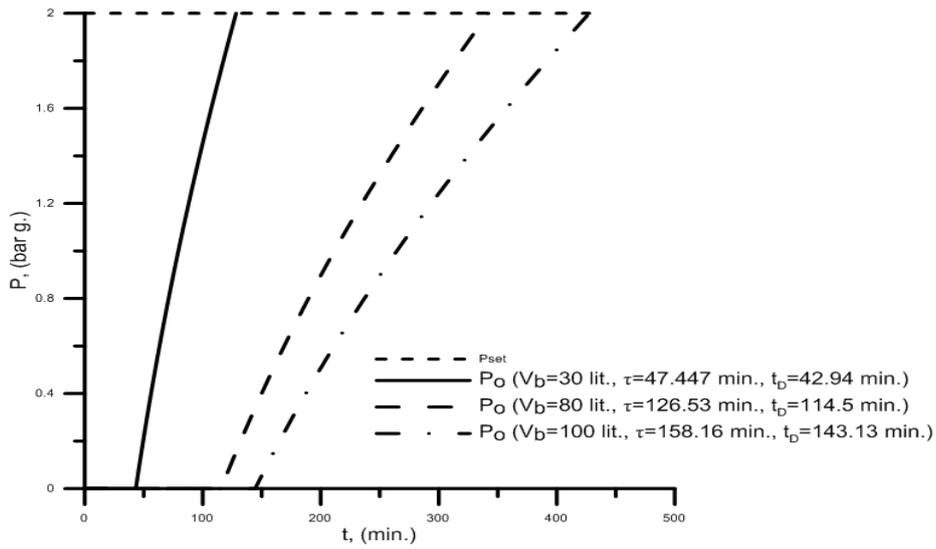**Fig. 6:** Steam generator pressure response for different values of void fraction

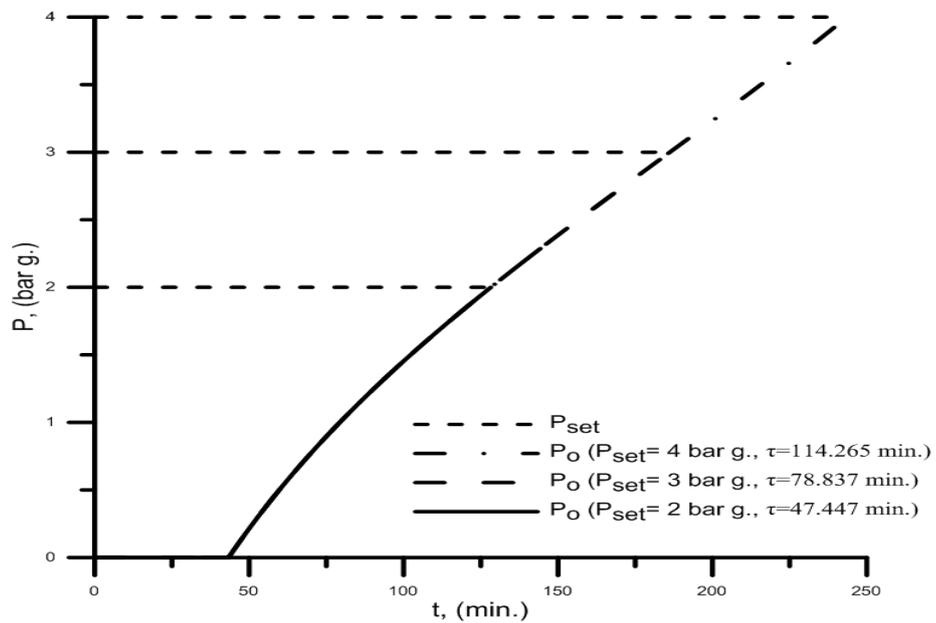**Fig. 7:** Steam generator pressure response for different values of boiler volume

Fig. 8: Steam generator pressure response for different values of pressure set point
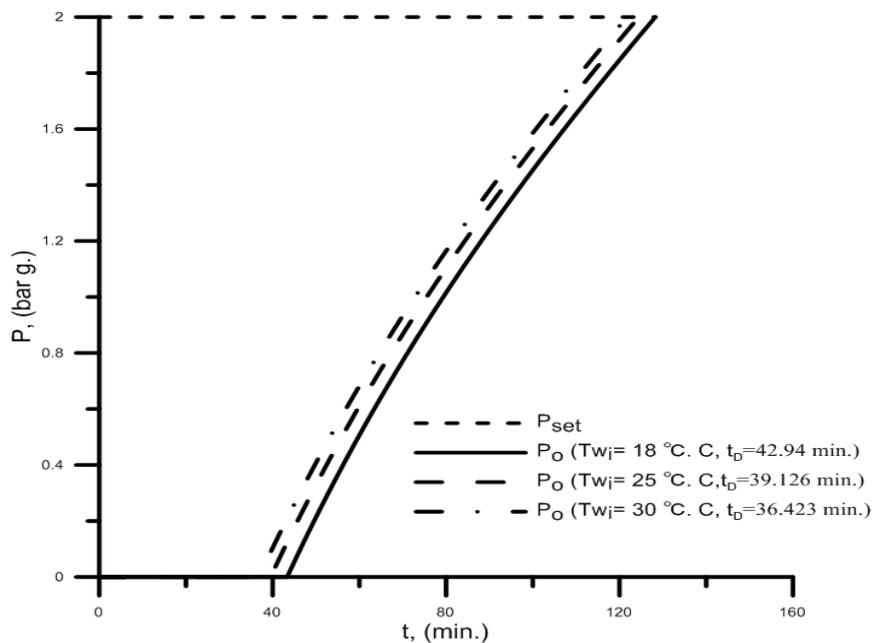

Fig. 9: Steam generator pressure response for different values of initial water temperature