An innovative control system of a hybrid tankless water heaters using LabVIEW

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Abstract. This paper presents an innovative control system of a hybrid tankless water heater that provides a rapid response to deliver hot water within a desired temperature range at lower energy consumption. The proposed tankless water heater provides a hybrid heating process that composes of a gas fired heater as primary heater and an electric heating system as secondary heater. LabVIEW designing software was used in designing the control system. A controller was designed using a PID controller which response with respect to given input parameter such as changes in water flow and the inlet temperature. Through alteration of heat source, this efficiently reduces the power consumption of the tankless water heater during low water demand, and eliminate overshoots. Simulation results demonstrated that the proposed system has performed efficiently in a range of water flow and temperature demand while reducing power consumption for about 30%.

1. Introduction

Majority of residential hot water production uses gas fired water heaters as it has the advantage of converting thermal energy to heat. Storage type or tank-based gas fired water heater is the most conventional water heater used for both industrial and residential application because of its capability to heat bulk of water at lower cost. Tank water heater works as simply as supplying cold water to the tank and injected at its bottom through a dip tube. As the water heats up, it naturally rises and is drawn off by a hot-water discharge pipe [1]. However, tank-based water heaters use a lot of gas for maintaining the desired water temperature in which it continuously fires the tank even if the demand of hot water is low. Tankless gas water heater (TGWH) gains the popularity as a replacement of tank-based heaters. It is the most efficient conventional method of generating heat from natural gas in a domestic hot water application [2]. At the rate of three gallons of hot water per minute, the TGWH has the capability to heat the water instantly compared to tank-based water heaters since a larger volume of water in a tank makes the tank-type heater to heat the water at a longer period of time [3]. One disadvantage of TGWH is the difficulty to produce stable hot water temperature as it is prone to large temperature swings. This is due to the changes in water flow, as it changes rapidly and unpredictable [4]. Majority of tankless water heater units are having fully modulating gas valves that can range from 10,000 BTU to 1,000,000 BTUs which limits the heating system at certain flow rate [5]. As the flow rate is inversely proportional to the outlet temperature for tankless water heaters, a very low flow rate may result overheating of water since the gas fired unit has a minimum flow limit. Contrarily, a temperature drops or a splash of cold-water
occurred when water demand increases rapidly. On the other hand, an electric powered water heater gains the popularity as it can be easily controlled. Compared to gas fired heater, an electric water heater power consumption is controlled by the voltage applied to its heating element [6]. Recent work conducted by manufactures for controlling of TGWH output temperature were not been published as research paper, but resulted as patents instead such as the use of blending valve for combining overheated water and cold water to produce blended hot water at predetermined temperature [7], a heating system that has a multiple chamber connected in series [8]. Few research papers are can be found in the literature discussing techniques of TGWH temperature output control. One of those controlling techniques was proposed by Haissig and Woessner using An adaptive fuzzy control (AFC) algorithm to regulate the domestic hot water temperature and central heating water of a combi-boiler [9]. Henze et. al. develop and build an TGWH that utilize model predictive control (MPC) to minimized the outlet temperature error [10]. Costa et. al. make a model of a tankless gas water heater that composes of a tank acting as a thermal capacitance, a mixing valve for mixing tanked water and heated water, and a bypass valve that is connected to the outlet of heater connected to the output aims to eliminate the outlet temperature overshoot [4]. Furthermore, despite of giving an accurate outlet temperature control, a gas fired water heaters release CO2 emission from burning of natural gas that is needed to reduce or eliminate in the future works [11]. In Table 1, CO2 emissions of heating water using natural gas, and electric resistance water heaters was presented. This clearly shows that electric water heaters greatly contribute CH4 and CO2 emission when using natural gas or coal as source of electricity more than those of Gas water heaters. Even though the use of renewable sources of energy are being develop for water heating, its current efficiency were not enough to overcome the conventional gas fired heater [12-13].

| Source of electricity | GHG  | Reference          | Natural gas water heater | Electric water heater |
|----------------------|------|--------------------|--------------------------|----------------------|
|                      |      |                    | Storage | Tankless | Storage | Tankless             |
| Coal                 | CH4  | Alvarez et al [14] | 0.82    | 0.6      | 0.2     | 0.19                 |
|                      | CO2  |                     | 86.5    | 63.6     | 256     | 243                  |
|                      | CH4  | Howarth et al [15]  | 1.38    | 1.02     | 0.2     | 0.19                 |
|                      | CO2  |                     | 86.5    | 63.6     | 256     | 243                  |
| Natural Gas          | CH4  | Alvarez et al.      | 0.82    | 0.6      | 0.97    | 0.93                 |
|                      | CO2  |                     | 86.5    | 63.6     | 125     | 119                  |
|                      | CH4  | Howarth et al.      | 1.38    | 1.02     | 1.3     | 1.23                 |
|                      | CO2  |                     | 86.5    | 63.6     | 125     | 119                  |

Due to the stated problems with regards to environmental impact, power consumption, and systems controllability of water heating technology a hybrid heating system was proposed that is capable of delivering water within a desired temperature range at lower energy consumption and CO2 emissions. This paper presents an innovative control system of a Hybrid tankless water heater (HTWH). A gas fired water heater is used as a primary heating element for high flow water demand, while an electric water heater is used as a secondary heater for maintaining the water temperature in a buffer tank during low flow demand. To accurately measure flowrate in high temperature areas, the differential pressure sensor was calibrated using artificial neural network. Furthermore, the PID controller is used as the main controller for the both heaters and recirculating pumps. The simulation of the proposed model was made through LabView design software.
2. Modelling HTWH Components

Figure 1 illustrate the schematic diagram of the HTWH. Combination of two heating element is present in this design for heating different flow demand. A flow demand causes a fluid to enter the water heater at inlet and exit water heater at outlet. At point 1, the water inlet temperature was measure and sends the signal to the controller for heat control. From point 1, water enters directly to point 2 and at point 6 if bypass is desired. Flow meter used to measure the rate of water entering the primary heater, signal from flow meter was sent to the both controller of heater. When in moderate and high demand of water it sends signal to the primary heater to give enough amount of heat to reached the desired temperature at the outlet. A sudden drop of flowrate tends to increase the outlet temperature in conventional water heater, while flow surge decreases the temperature at the inlet. To resolve this issue, a thermal compensating differential pressure switch is used to detect surge of flow or sudden drop of flow between the point 6 and point 4, it signals the controller to turn on or off the primary heater or secondary heater. In a moderate demand of flow, secondary heater was off or at the lowest power setting to just maintained the heat at the buffer tank. When the demand of flow was high, both heater functions to generate give the desired temperature rapidly. And at when flow of water is too low, the primary heater was turned off while the secondary heater was on, also recirculation was added in the design to absorb the remaining heat from the primary heater, this would also resolve the problem of having cold sandwiches or the stack water that cooled down at the pipe while heater is not in used.

To develop and simulate HTWH controller, a modelling methodology was established in which individual parts of each internal component are modelled, describing thermal, fluid and mechanical dynamics. Then models of each component are then interconnected which builds the whole HTWH system. For the fluid component, mass conservation law is applied to for controlled volume given by the equation

\[ \dot{m}_{in} = \dot{m}_{out} \tag{1} \]

where \( \dot{m}_{in} \) is the mass flow rate inlet and \( \dot{m}_{out} \) is the mass flow rate outlet. Mass distribution inside the system where split into the three-way valve for the recirculation, bypass and buffer tank. The equation of mass flow rate split by the bypass line is written as

![Figure 1. Schematic of a HTWH](image)
\[ m_{in} = m_a + m_b \] (2)

where \( m_a \) and \( m_b \) are the mass going to heat cell and bypass line. A check valve is used to avoid counter flowing of water in the recirculation line. During overshoot the bypass line and recirculation line are open for tempering of water outlet, so the total mass entering the heat cell during overshoot is the addition of flow of recirculation and inlet flow deducting the bypass flowrate given by the equation

\[ m_h = m_a + m_c - m_b \] (3)

where \( m_c \) is the mass flow rate from the recirculation line.

2.1. Heat Cell
The thermal dynamics of the heat cell is based on the energy conservation equation for the control volume under analysis. Only the internal energy variations are considered, the kinetic and gravitational potential energy variations are assumed negligible and a constant mass inside each control volume is considered.

2.1.1. Primary Heat Cell. Primary heat cell mathematical model is derived from the energy conservation equation

\[ Q = \dot{m}_h C_p (T_f - T_i) \] (4)

Where \( Q \) is the heat needed to rise the temperature inlet, \( T_i \) into the final temperature, \( T_f \) at mass entering the heat cell, \( \dot{m}_h \). Using the specific heat capacity of water, \( C_p \). Figure 2. Illustrates the case structure of primary heat cell in LabView. Case structure is used as to turn on and off the heater whenever a boolean statement is true which is connected to the amount of flow at the inlet line.

2.1.2. Secondary Heat Cell. For Secondary Heat cell, uses the same energy equation as the primary heater. Secondary heater will turn on by a boolean statement connected into the flow sensor at the inlet line. For low demand of flow the boolean statement is false which turns on the secondary heater. The temperature inlet, \( T_i \) of the secondary heater are the total heat absorb by the recirculating line and the temperature of water inlet.

2.2. Recirculation and Bypass line
Bypass line was designed to split the water inlet to two part. At the end of the line cold water and hot water meets which tempers the outlet water at the desired water temperature. Bypass valve is either
manual or automatically operated. The final temperature from the model of the bypass mixing valve is given by the equation

\[ T_m = \frac{(m_b T_i + m_h T_f)}{(m_b + m_h)} \] (5)

Where \( T_m \) is the temperature at the mixing valve, and \( T_f \) is the temperature from the outlet of the heater. Case structure of the mixing valve was shown in figure 3, it is turn on when the boolean statement is true which means the control valve for the bypass line was manually controlled, while false case structure where made by just connecting the input \( T_f \) into output \( T_m \).

Recirculation take effect when an overshoot was occurred or during low flow demand. Mixing of heated water and water inlet happened during recirculation, this for absorbing the excess heat from the primary boiler, or reusing the excess heat during overshoot. Case structured with formula node was used for another mixing valve using the equation 5.

2.3. Sensors

Sensors are one of the critical components of the HTWH. This this heating system two thermal sensors are used to monitor the temperature from the inlet, mixing and outlet of the system. each sensor sends signals to the controller for an accurate feedback. For measuring the flow and pressure of the system, three pressure sensors are used. Two sensors are used for measuring the flow rate of inlet and mixing valve while the other one is a Differential pressure switch sensor which has the capability to detect surge flow or flow drop. Each sensor sends signal to the main controller for the selection of which heater will turned on. A pressure sensor with thermal compensation is a must feature for the system since sensors has direct contact with the measuring fluid.

2.3.1. Flow Measurement.

Flow measurement calculation was based on the differential pressure measured by the DP sensor. As shown in Fig. 4 the DP sensor is used in a straight pipe attached at the both pressure side separated by an orifice. For DP sensors placed at the mixing valve, a specially designed sensor was used to compensate the effect of high temperature. From the reading acquired by hall sensor the differential pressure will be computed. The formula used in this simulation for computing the flowrate by means of measured pressure difference is based on the ISO standards ISO 5167-1 and 5167-2 for measuring steady flow. Given by this formula

\[ Q = C_d \sqrt{\frac{2 \Delta p}{\rho}} \times \frac{A_2}{\sqrt{1 - \left(\frac{A_2}{A_1}\right)^2}} \] (6)

where \( \Delta p \) is the differential pressure between high pressure and low pressure side, \( \rho \) is the fluid density and \( C_d \) is the coefficient of discharge. The discharge coefficient \( C_c \) is given by empirical formulas, which
depend on the ratio of the orifice bore and pipe inside diameter. Hence the density of the fluid varies as temperature increases due to thermal expansion of fluid. This may result to an additional error to the flowrate reading as in Equation 6 the density is required. To accurately measure the flowrate at different temperature the DIPPR105 equation 7 is used for computing the exact density of fluid [16]. The DIPPR105 equation is written as

\[ \rho = \frac{A}{T^{1+\frac{C}{D}}} \]  

where T is the temperature of water in Kelvin which has 273 K to 648 K temperature limit and A, B, C, and D are empirical constant with a value of 0.14395, 0.0112, 649.727, and 0.05107 consecutively.

2.3.2 DP sensor calibration. The calibration of pressure transmitter using ANN is shown in Fig. 5. In this work the training sets used to train the neural network is from the experimental data of Sinha and Mandal 2018 [17]. The desired value of the hall voltage was a result of the experiment at applied constant pressure at a room temperature of 27°C. The inputs to the neural network are the Hall voltage from hall sensor and varying temperature, and the ANN output is corrected output Hall voltage.

ANN is trained in Neural Fitting tool in Matlab using Levenberg-Marquardt backpropagation algorithm to calibrate the sensor since the reading of DP sensor without calibration results an increasing error as
temperature increases. The performance of calibration was shown in table 2. Wherein the DP sensor error was reduced from 3.51%-13.14% into 0.75% - 1.79%. This will give an accurate value for the controller to calculate the power needed to supply in order to meet the desired outlet temperature.

**Table 2. Effect of High Temperature on DP sensor reading.**

| Temperature | DP reading before calibration | DP reading after calibration | True Value | difference | % error before calibration | % error after calibration |
|-------------|-------------------------------|------------------------------|------------|------------|---------------------------|--------------------------|
| 15°C        | 17.61                         | 18.39                        | 18.25      | 0.78       | 3.51%                     | 0.75%                    |
| 20°C        | 18.21                         | 18.25                        | 18.25      | 0.04       | 0.20%                     | 0.02%                    |
| 27°C        | 18.42                         | 18.26                        | 18.25      | 0.15       | 0.95%                     | 0.14%                    |
| 30°C        | 18.57                         | 18.27                        | 18.25      | 0.28       | 1.75%                     | 0.23%                    |
| 35°C        | 18.73                         | 18.31                        | 18.25      | 0.42       | 2.64%                     | 0.32%                    |
| 40°C        | 19.04                         | 18.33                        | 18.25      | 0.71       | 4.35%                     | 0.45%                    |
| 50°C        | 19.41                         | 18.36                        | 18.25      | 1.05       | 6.34%                     | 0.60%                    |
| 60°C        | 19.79                         | 18.40                        | 18.25      | 1.39       | 8.46%                     | 0.84%                    |
| 70°C        | 20.21                         | 18.47                        | 18.25      | 1.73       | 10.72%                    | 1.23%                    |
| 80°C        | 20.65                         | 18.58                        | 18.25      | 2.07       | 13.14%                    | 1.79%                    |

2.4 PID Controller

For the PID component, the feedback power is calculated based on the desired input temperature and output of process variable e.g. outlet temperature. PID output was set at from 3000 to 60000 watts based on the maximum performance of the TGWH and 0 to 2000 watts based on the maximum power output of the EWH. PID gains were automatically tuned from the LabView PID autotuning block.

3. Simulation

Individual components were modelled separate in LabView, by connecting each component models a HTWH formed and used in simulation. As illustrated in Figure 6. The HTWH model was enclosed by a while loop for an infinite simulation time frame. The volume flow rate was adjusted manually by adjusting the control knob during the run time. Adjusting knob in the scale of 0-4 makes an opening of the valve which enables water to flow for a range of 0 – 10 liters per minute. The initial water temperature is a constant parameter in the simulation, it was set according to the average temperature of tap water in a tropical country that is 27 °C. The set-point temperature was set to be at 50 °C, above the average hot shower temperature. A monitoring panel was shown in figure 7. In the front panel the temperature of inlet and outlet was illustrated by red-colored progress bar, a default numeric indicator of LabView for indicating temperature. Three knobs are place for the adjustment of heated water volume flow rate, bypass flow rate and desired temperature setting. Two led light was also placed to indicate whether the heater is on or off, and which heater is running. And lastly a flow gauge was placed to monitor the volume of water flowing through the heater.
Figure 6. HTWT LabView block diagram

Figure 7. HTWT LabView front panel

4. Results and Discussion
Simulation results shows that the model response with less overshoots on the given flowrate changes as illustrated in Figure 8. Turning on of bypass valve during overshoots helps the system to reduce the high outlet temperature output rapidly, while recirculation of high temperature water throughout the system helps the secondary heater to maintain the desired temperature in a low flow demand scenario. The power consumption of the HTWH was shown in Figure 9. The red line indicated the power consumption of the primary heater while the blue line indicates the secondary heater consumption. It clearly shows that when the flowrate was below 5 lpm, the primary heaters shuts down then the secondary heater takes its place. As a result, it saves power for about 30% and lessen the amount of CO$_2$ emission from the primary heater.
9

Figure 8. Simulated HTWH outlet temperature response to a water flow rate step.

Figure 9. Simulated HTWH power consumption.

5. Conclusion
In this work, an innovative control system was developed for a Hybrid tankless water heater for the improvement of conventional tankless water heater. A hybrid heating system were composed of two heating cells specifically a gas fired and an electric operated heater that are controlled using PID controllers. Simulation results shows that the response of the model has able to give the desired water temperature at the different flowrates and responds within short period of time. Through recirculating flow and opening of bypass valve the overshoots were lessened. Moreover, the proposed control system has able to save energy by altering the use of heat cells in high and low flow demand for about 30% and lessens the CO$_2$ emission from the gas fired heater. For the future work of this research, the next task will be a research on an advanced controller which has able to predict the flow demand ahead of time for an advance heating method.
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