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Design and Implementation of Affordable Residential Hot Water Systems

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Abstract
With the increase in the Gross Domestic Product of Bangladesh and her rising middle class citizens, it has been noticed that a significant portion of the population in the capital city of Dhaka and elsewhere are using luxury commercial goods such as personal automobiles, washing machines, air conditioners, dishwashers, and hot water systems. Traditionally, hot water was only available by heating tap water in a stove, and had wide variety of usage such as washing clothes and bathing during cold weather. However, currently more and more people are installing water heating system in their homes to provide hot water supply. The paper outlines an affordable low cost and environmentally friendly design of a residential water heating system. The system has been successfully prototyped for a small 10 liter unit with the capability to scale up to multiple units each capable of holding up 100 gallons.

Keywords: *Water Heaters, Microcontrollers, Embedded Systems.*

I. Introduction

Since 2002, there has been an exponential increase in the Gross Domestic Product (GDP) and the GDP per capita in Bangladesh. This has been possible due to few major shifts in the Bangladeshi economy from the previous century: namely the rise of the readymade garments (RMG) industry, the increase in the Foreign Direct Investment (FDI), an increase in remittances from Bangladeshi nationals living abroad, and the implementation of the microcredit system for poor and rural entrepreneurs. In fact Bangladesh have enjoyed above 5% growth rate in her GDP for more than one decade (A. J. F. Sousa *et al*, 2017). This resulted in an increase in disposable income for a many people and the rise of the middle class in urban areas. As such, the Bangladeshi middle class people have started consuming more luxury goods; middle class families now own personal automobiles for transportation, consume luxury goods such as washing machines for washing their clothes, air conditioners in their bedrooms to beat the summer heat, dishwashers to clean their dishes, and finally a hot water system to supply hot water for washing clothes, cleaning, and bathing during cold weather. What was previously done by manual labor (i.e. servants and maids) is slowly being replaced by consumer electronics. It is fact that all new residential houses comes with points for broadband and cable connections, air conditioning outlets, drainage points for dishwashers and washing machines, and space allocated for hot water tanks or geysers. Older homes are jury-rigging geezers close to bathrooms to avail of this new convenience. The paper will detail the design of an affordable low cost hot water supply system for a multistory residential building utilizing environmentally friendly technologies.

II. Types of Hot Water Systems

Water heating is a thermodynamic process that uses an energy source to heat water above its initial temperature. Typical domestic uses of hot water include cooking, cleaning, bathing, and space heating. Water is traditionally heated in vessels known as kettles, cauldrons, pots, or coppers. These are metal vessels that heats a batch of water and do not produce a continual supply of heated water at a preset temperature. The temperature varies with the consumption rate, becoming cooler as flow increases.

Appliances that provide a continual supply of hot water are called hot water heaters, hot water tanks, boilers, heat exchangers, or geysers. Fossil fuels (natural gas, liquefied natural gas, oil), or solid fuels

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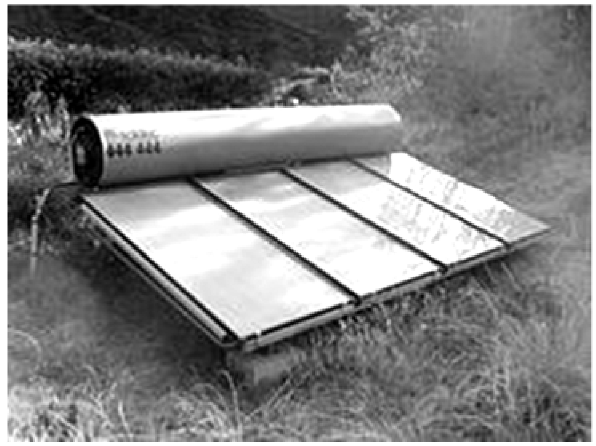
are commonly used for heating water. These may be consumed directly to heat the water or be used to generate electricity, which can then be used to heat the water. Electricity to heat water may also come from any other energy sources such as nuclear power or renewable energy. Alternative energy such as solar energy, heat pumps, hot water recycling, and geothermal heating can also heat water, often as combination with backup systems powered by fossil fuels and electricity (Domingo, 2010).

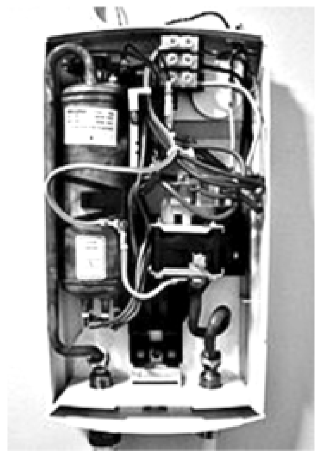
Densely populated urban areas of developed countries also provide district-heating of hot water. In such systems, the supply energy for water heating and space heating come from waste heat from industries, power plants, incinerators, geothermal heating, and central solar heating. Actual heating of tap water is performed in heat exchangers at the consumers' premises. Fig. 1 shows the various types of water heaters. Fig. 1a ~ 1c show tank based systems where the water is heated and stored in a tank for future use, and Fig. 1d and 1e show tank-less systems where the water is heated as it passes through the pipes. Electricity, natural gas, and solar (thermal) power can be used to heat the water.

a) Electric Water Heater with Tank

b) Gas Powered Water Heater with Tank



c) Solar Water Heater with Tank



d) Tank-less Electric Water Heater

e) Electric Shower Head

Figure 1: Various types of Water Heaters (M. A. Pachkawade *et. al.*, 2013)

Tank based systems are the most common types of water heating system. Gas powered water heaters would be more practical in Bangladesh since she is blessed with lots of natural gas. However, due to a heavy demand from a very large population, the supply of gas is not constant, and moreover, the gas supply is prioritized for industries; therefore, gas powered systems need to be supplemented by a solar powered system to not put undue stress in the gas supply. Newer designs include the tank-less system which instantly heats the water as it flows through the device, and they do not retain water internally. Tank-less water heaters can be installed throughout a household at more than one point-of-use (POU).

There are advantages and disadvantages of both types of systems. Tank based systems have the advantage of using gas or electricity at a relatively slow rate, and storing the heat for later use. In fact, the heaters can be turned on during non-peak hours when electricity is supplied at a cheaper rate to the household. But the problem with tank based system is that over time the water will cool down (even with sufficient insulation), and the heater needs to be periodically turned on to heat the same water repeatedly. Additionally, when there is heavy use of the hot water, it exhausts the hot water supply requiring a significant delay before the hot water is available again. On the other hand, tankless system supply continuous flow of hot water and potential energy savings due to only heating water when required. However, to have the hot water on demand requires a very high powered heater and because there is no storage for the hot water. Furthermore, multiple tanks-less systems are required because they have to be installed on every water outlet in the household where hot water is required. This makes the tank-less system a very expensive, and thus these systems are not feasible for practical implementation in Bangladesh. Therefore this paper will deal with tank based residential hot water supply system.

III. Constraints of Hot Water Systems

Any hot water system must enforce the following conditions: the hot water must not cause damage to human skin, the water must not be contaminated with microbial organisms, and finally the pressure inside the heater must not exceed beyond a certain point so as to cause explosion in the heater tank or in the plumbing system through which the water is piped. These constraints require special consideration in the design of the control system of the water heater.

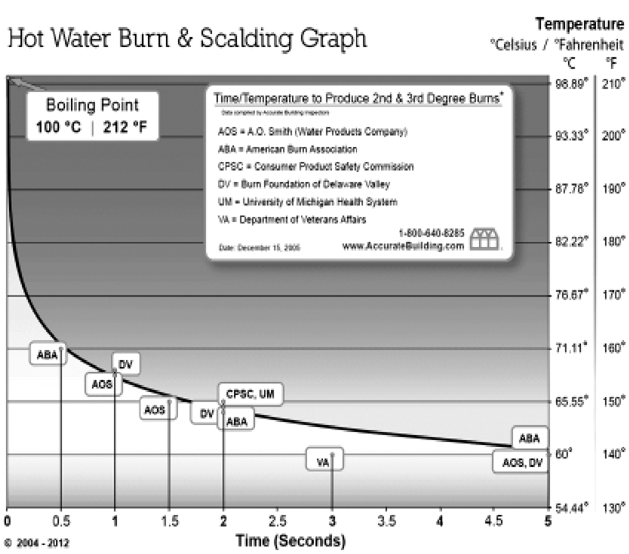


Figure 2: Hot Water Burn and Scalding Chart (A. Ubell *et at.*, 2004)

First and foremost, let us consider the issue of damage to human skin. Hot water can cause thermal burns or "scalding". This is because human skins burns quickly at high temperature, for example, it takes less than 5 seconds to suffer a second degree burn at water temperatures above 60˚C, as shown in the graph in Fig. 2. On the other hand, it takes a full minute or more at temperatures below 53˚C. Human beings are typically equipped with reflexes to pull quickly away from very hot surfaces, but the very old and the very young may not have well developed reflexes, therefore the water that comes out of the tap or the shower cannot exceed 55˚C to give them sufficient time to pull away in case they accidentally come into contact with the hot water.

The second issue to consider is the risk of bacterial contamination, particularly by Legionella, a pathogenic group of Gram negative bacteria that can survive at water temperatures up to 50˚C, and flourish (i.e. grow and multiply) at temperatures in the range of 30˚C to 45˚C (CDC, 2016). Therefore it is recommended that hot water not be kept below 50˚C. The above two conditions places a constraint on the water temperature to between 50˚C to 55˚C.

Finally, there is the issue of explosion. Any high pressure or high heat systems can have potential to explode. Explosion in hot water tank can happen due to steam build up. Hot water tanks are usually maintained under high pressures required for plumbing systems. Without sufficient pressure, the water from the tank will not flow smoothly out of the faucet. High pressure also increases the boiling point of water; water that would be vapor normally at atmospheric pressure exists as liquid inside the tank. Even so, there is intermittent build up of steam which needs to be released. This is achieved via a temperature and pressure relief (TPR) valve, similar to what is found in pressure cookers. TPR valves, due to improper maintenance, can get rusty and be release steam/water during pressure buildup. Thus the pressure inside the tank must be constantly monitored. The pressure inside the tank will be monitored and if it rises above 0.5 atmospheres (~50kPa), the heater must be shut down.

IV. Low Cost Hot Water System Design

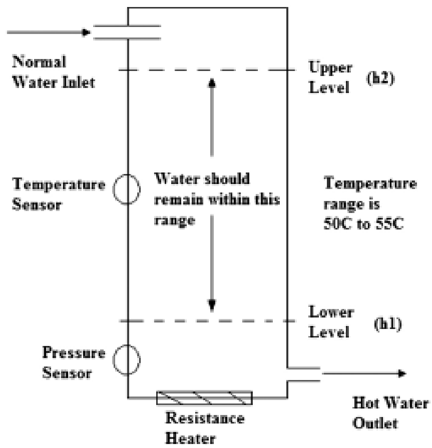


Figure 3: Structural Design of the proposed Hot Water Tank (S. Biswas *et al.*, 2016)

This section will describe the design and implementation of a low cost hot water supply system. The design consist of a resistance water heater connected to a mixer situated at the bottom of the hot water tank, a temperature probe situated at the mid-point of the hot water tank and a pressure sensor situated at the bottom of the tank as shown in Fig. 3.

The pressure sensor will monitor water level by comparing the differential water pressure in the tank with atmospheric pressure. The water level must be kept between the two level set points. The upper level set point ensures that the tank never overfills, and the lower level set point ensures that the water heater is always submerged. It is important that the heater is submerged, because turning on the heater in an empty tank will result in the heater or the tank casing being damaged. This would present a safety hazard. The mixture will ensure that the temperature of the water inside the tank remains homogenous. The resistance heater has to be situated below the low level water line in the tank to enable convection heating of the water.

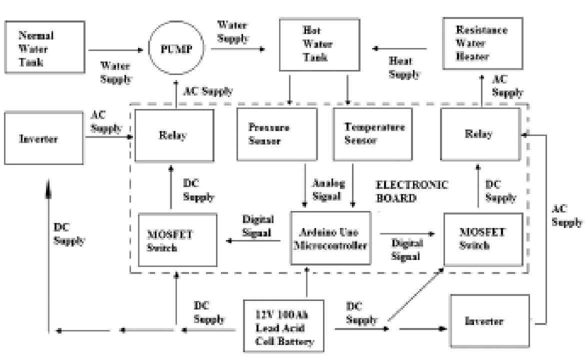
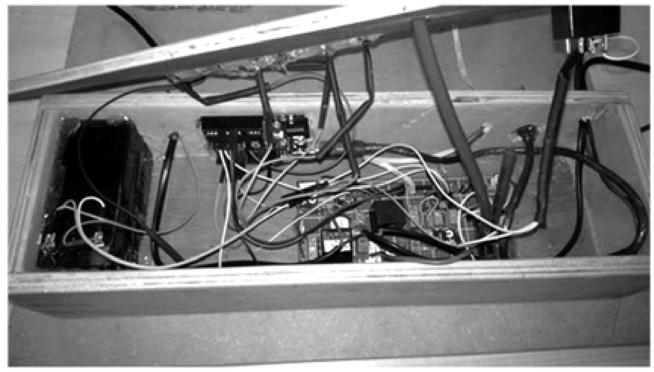
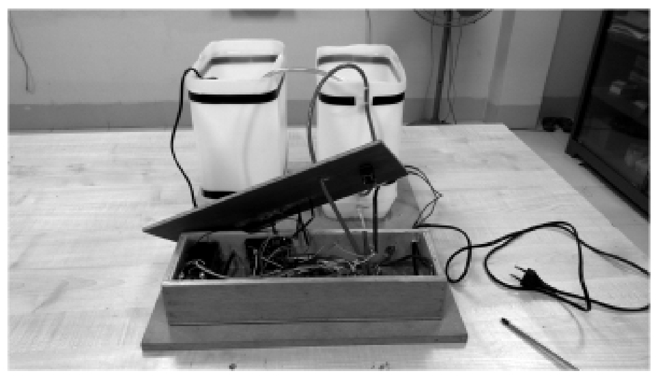


Figure 4: Schematic Diagram of the Hot Water Tank Control System (S. Biswas *et al.*, 2016)

The water pump will be activated if the water level falls below the low level set point to pump in more water; if the water level rise beyond the high level set point, the water pump will be deactivated. Similarly, if the temperature of the water falls below 50˚C, the resistance heater will be turned on to heat the water; if the temperature rises above 55˚C, the resistance heater will be turned off. Fig. 4 shows the electronic design of the hot water tank control system and Fig. 5 shows the implemented hardware.



(a) Internal wiring of controller



(b) Complete System

Figure 5: Prototype of the Hot Water Tank and Control System (S. Biswas *et al.*, 2016)

V. Controller Parameter Calculation

This section will discuss the control parameters involved in the control action. First, it should be mentioned that the ADC module of the embedded controller is an 8-bit module, with a reference voltage of 5V. Therefore the output of the ADC module is given as:

$$\text{Output} = V_{IN} * 256 / 5 \tag{1}$$

According to equation (1), ADC module detects input voltage in increments of ~19.53mV. This module will be used to detect the analog output of the pressure sensor and the temperature sensor.

The output of the temperature sensor will be an analog voltage in the range of 0V to 5V based on the equation (2).

$$V_T = 10mV/^\circ C * T \qquad (2)$$

Where T is the water temperature in ˚C. According to equations (1) and (2), for the lower level temperature of 50˚C, the output of the sensor will be 0.5V and the ADC output will be 25.60; for the upper level temperature of 55˚C, the output of the sensor will be 0.55V and the ADC output will be 28.16. Thus, the controller needs to turn on the resistance heater if the ADC value falls below 25, and turn off the resistance heater if the ADC value rises above 29.

The output of the pressure sensor will also be an analog voltage in the range of 0V to 5V based on equation (3).

$$V_P = V_S * (0.018P + 0.04) \qquad (3)$$

Where VS is 5V and P is the pressure taken in kPa. Now the upper and lower level set points will depend on the tank size, but for the prototype the lower level set point is at 0.05m (~2 inches) and the upper level set point is 0.2m (~8 inches). The water pressure is given by the following formula:

$$P = \rho g h \qquad (4)$$

Where ρ is 1000 kg/m^3 for water, and g is 9.81 m/s, and h is the water level in m. According to equations (1), (3), and (4), the water pressure when the water level is at the lower set point will be 0.490 kPa, the output of the sensor will be 0.244V, and the output of the ADC will be 12.50; the water pressure when the water level is at the upper set point will be 1.962 kPa, the output of the sensor will be 0.377V, and the output of the ADC will be 19.28. Thus, the controller needs to turn on the water pump when the ADC output falls below 12 and turn on the pump when the ADC output rises above 20. There is one final control action that is required; namely, the resistance heater will not be allowed to turn on if the ADC module monitoring the pressure sensor shows an output of less than 12, regardless of if the water temperature falls below 50˚C. This is to ensure that there is a minimum level of water inside the tank before the heater is turned on, and therefore to prevent damage.

VI. Conclusions

The paper describes the prototype design of a low cost hot water tank system. The controller efficiently monitors the water level and temperature and maintains them within their designated set points. While the pump action is quick enough to demonstrate, the heating effect is slow for a full tank, therefore it was demonstrable only for low water levels.

The system can be scaled up in quantity, either increasing the size of the water tank, or connecting multiple hot water tanks to the main water supply tank. However, in that case, the water level in the main water supply tank must also be monitored to ensure that it has sufficient water to supply to the hot water tank. If the main water tank does not have sufficient water, then the water pump supply to the hot water tank will not be turned on, in order to protect the pump.

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