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Modelling and Simulating Rate of Heat Transfer in Different Lagging Materials and Temperature Variation with Time

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Abstract- Heat storage is the process by which thermal energy is stored in a medium and is prevented from being loss to the environment through the application of lagging materials. Hot water is a means by which thermal energy is being stored in water heater and can be used when situation demands if properly insulated. In this study, an insulated 50 litre capacity water tank is developed, and its energy storage performance was analysed through numerical simulation method that employed MATLAB and COMSOL multiphysics. Fiberglass, cellulose, Mineral wool, straw bales and polyurethane foam are the insulating materials that their rates of heat loss through them were studied. The 3D temperature distribution, thermal resistance and rate of heat loss across the container were determined using numerical method when water temperature was kept at 70°C. Also effect of insulating material thickness on rate of heat loss was study. From the results obtained from MATLAB, with15mm thickness the time taken for cellulose, fiberglass, mineral wool, straw bales, polyurethane foam to prevent heat loss from 70°C to 22°C are 750 min, 670 min, 670 min, 290 min and 1250 min respectively. Also with 20mm thickness the time taken for cellulose, fiberglass, mineral wool, straw bales, polyurethane foam to prevent heat loss from 70°C to 22°C are 1200 min, 1050 min, 1050 min, 470 min and 2000 min respectively. It was evident from the result that the rate of heat loss could be prevented increasing the thickness of the lagging material. The material that has the highest thermal resistance was found to be polyurethane foam due to the time in which it will take the water to be at room temperature. The rate of heat loss, thermal distribution, thermal resistance and rate of heat transfer for polyurethane foam was found to be 10.92J, 212.5257K/m, 1.4679K/W and 171.351W respectively.

Keywords*- Insulated Water Tank, Mumerical Simulation, Thermal Resistance, Heat Transfer, Temperature*

I. Introduction

Water is greatly used residentially and industrially. It can be used for drinking, cooking, bathing, washing, laboratory use, agricultural use and so on. Water can be heated either electrically or through solar energy. Electric heating is any process in which electrical energy is converted to heat energy for the purpose of space heating, cooking, water heating and industrial processes. Appliances that provide a constant supply of hot water are called water heaters such as hot water tanks, boilers, heat exchangers, geysers. However, heating of water requires energy which is at a cost. The significant increase in demand for energy by several emerging nations has driven the global energy consumption to unprecedented levels. As a result, the cost of energy has reached new levels and is expected to continue to rise. The ramifications of this large increase in energy cost, will pose serious challenges to the economies of most developing nations [1].

The temperature of water in hot water storage medium such as flasks changes gradually due to the type of lagging materials used. Minimizing heat losses in hot water were the goals of different researchers over the past years. Some researchers investigated different hot water system, use pattern and load while some studied insulation to reduce losses, thermal conduction through tank with different wall thickness [2, 3, 4, 5, 6, 7, 8, and 9]. The more thermal insulation the better since it reduces standby heat loss. Water heaters are available with insulation ratings ranging from R-6 to R-20. The R-value of a material is its resistance to heat flow and is an indication of its ability to insulate. It is used as a standard way of telling how good a material will insulate. The higher the R-value, the better the insulation [10]. Insulating materials can be classified according to their chemical or their physical structure, and the most widely used insulating materials are classified as inorganic, organic, combined material and sustainable materials.

In this way, many researchers developed and enhanced the performance of insulated water tank and however, the thickness of the insulation layer or PCM layer is chosen arbitrarily. Increasing the thickness of the insulation layer reduces the loss of stored thermal energy, and on the other hand, it raises the cost of the water tank. An optimum insulation layer thickness is required to maintain the stored thermal energy relatively at low cost.

Factors affecting heat loss in a storage tank are mass of water, size of the tank, air pressure, color of material, relative humidity. The forms of heat loss in storage tanks are conduction, convection and radiation [10]. Due to colder temperatures, storage tank water heaters can experience greater heat losses particularly if they are situated in poorly insulated or unconditioned spaces [11].

To solve problem of heat loss in water heater, researchers have employed experimental and numerical methods to investigate it and suggest solution to it. The prime reason for developing a simulation is that the cost of experimenting with the actual system is prohibitive. Simulation is a numerical technique for conducting experiment on a digital computer which involves certain types of mathematical and logical relationship necessary to describe, the behavior and structure of complex real world system over extended periods of time. Simulation can provide an experimental system for designers to investigate behavior under a variety of different circumstances, or it may be used to provide a teaching aid for the system being investigated.

Several methods have been proposed to describe how heat transfer takes place in different lagging materials. The purpose of this project work is to provide a model and simulate the rate of heat transfer in different lagging materials and temperature variation with time. The objectives of this project are to determine the rate of heat transfer from the liquid to the lagging materials and evaluate rate of heat loss for different lagging materials.

II. MATERIALS AND METHOD

The proposed model is based on one dimensional energy and heat transfer equation. The steady energy and heat transfer equation under the given boundary condition were solved using the modified version of the standard partial differential equation (PDE) solver in MATLAB R2009b and COMSOL MULTIPHYSICS was used to show temperature distribution inside the hot water storage tank, calculate the rate of heat transfer to the arc length and also how each lagging materials retains heat.

A. Equation Formulation

To derive the material model for the rate of heat transfer in an hot water tank, the following assumptions will be made:

1. One dimensional steady state condition
2. No internal heat generation
3. Heat loss by conduction only
4. Direction of heat flow is radial

1) Energy and Heat Transfer Equation

Based on the cylindrical geometry assumptions the equation for the energy and heat transfer equations within the material, the general equation for heat transfer in a cylinder Equations [12]

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \emptyset^2}+\frac{\partial^2 T}{\partial Z^2}+\frac{q}{k}=\frac{1}{\propto}\frac{\partial T}{\partial t} \quad (1)$$

The rate at which heat is conducted across a cylindrical surface in the solid may be express as

$$q=-KA\frac{dT}{dr}=-K(2\pi rl)\frac{dT}{dr} \quad (2)$$

Considering a hollow cylinder made of materials having constant thermal conductivity and insulated at both ends and let r_1 and r_2 be the inner and outer radius respectively and T_w and T_{amb} are the temperature of the water and outer ambient temperature respectively while K is the constant thermal conductivity within temperature ranges.

2) Initial and Boundary Conditions

a) Initial conditions

Initial conditions are as given

$$T = T_w,\ r= r_1 \quad (3)$$

$$T = T_{amb},\ r = r_2 \quad (4)$$

b) Boundary Conditions

$$T_w= CInr_1+C_1 \quad (5)$$

$$Tamb = CInr_2 + C_1 \quad (6)$$

To determine the time taken for the water to cool down

$$t=\frac{MCp(Ts-Tf)}{Q} \quad (7)$$

$$Q=A[\frac{(Tamb-Tw)}{\left(\frac{e}{K}+\frac{1}{h}\right)}] \quad (8)$$

Where t is the time taken, m is the mass of water, T_s is the initial temperature of water, T_f is the final temperature of water which is the room temperature of the environment, Q is the quantity of heat loss, A is the total outside area of the container, e is the thickness of the insulation, K is the thermal conductivity of the insulator, H is the height of the container, C_p is the specific heat capacity of water

B. Numerical Parameters

The following are the values of the thermo physical properties of the materials used to obtain the experiment

TABLE I. INSULATING MATERIALS AND THEIR THERMAL CONDUCTIVITY

Materials	Thermal conductivity k (W/mk)
Fiberglass	0.04
cellulose	0.035
Mineral wool	0.04
Straw bales	0.09
Polyurethane foam	0.021

C. Design of the Hot Water Storage Tank

The capacity of the hot water storage tank is assumed to occupy 50 liters of water

50 liters = $0.05m^3$

$$density=\frac{mass}{volume} \quad (9)$$

Density of water is $1000kg/m^3$

$$1000=\frac{mass}{0.05}$$

Mass = 50kg

Area = πr^2

For the cylinder let assume D = 0.75H

$$H = \frac{D}{0.75} = \frac{2r}{0.75} \quad (10)$$

Volume of a cylinder = $\pi r^2 h$

In centimeter: $50 \times 1000 = 3.142 \times r^2 \times \frac{2r}{0.75}$

r = 18.138 cm which is 0.181m

Substituting our r back in equation 3.33

$$h = \frac{2r}{0.75} \quad (11)$$

But for more space the height will be 50cm which is 0.5m

Considering the thickness of the insulating material to be 10 cm.

III. RESULT AND DISCUSSION

A. Theoretical Analysis

After the values of D, H, and M were obtained. Equations were solved by using a numerical code written in MATLAB to obtain heat loss in each material and temperature distribution inside the hot water storage tank, COMSOL MULTIPHYSICS was used to calculate the rate of heat transfer to the arc length and also how each lagging materials retains heat. For numerical simulation, temperature of the water in the container was kept at 70^0C and the thickness of each insulating material was 15mm thickness. The material used for the internal coating and the external coating is stainless steel 316.

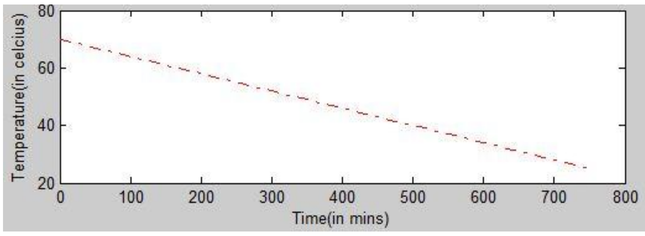
B. Results of Rate of Heat Transfer for Different Lagging Materials

The variation of the rate of heat transfer between the materials was obtained. The time it will take each material to prevent heat loss before the water gets to its room temperature at constant insulation thickness and the same surface area was determine as it was shown in fig. 1.

From this results it can be seen that it took cellulose 750 min, mineral wool 650 min, fiberglass 650 min, polyurethane foam 1250 min, straw bales 290 min before the temperature gets to room temperature. It was discovered that polyurethane foam has the highest thermal resistance at constant thickness and surface area.

C. Effect of the Variation of the Thickness of Polyurethane foam

Effects of variation of thickness of polyurethane foam between 15 mm and 20 mm was studied for hot water temperature of 70^oC. The results are presented in figures 2.



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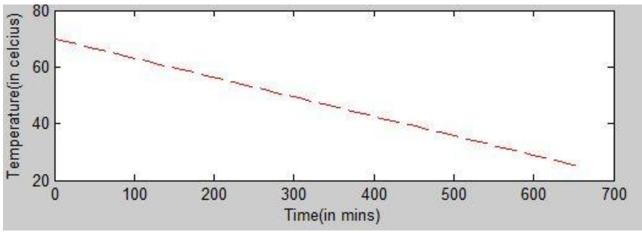

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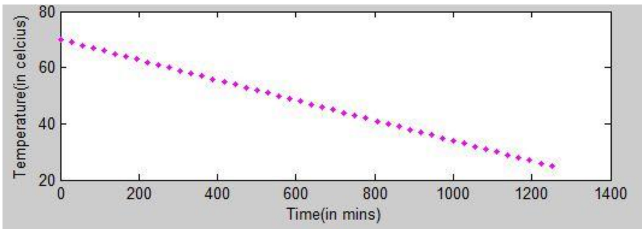

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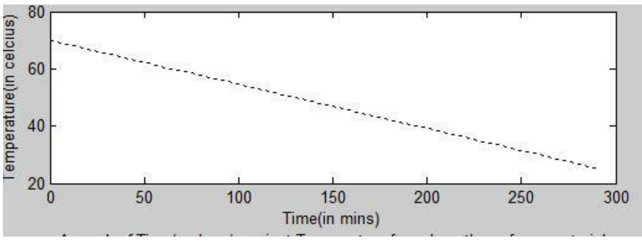

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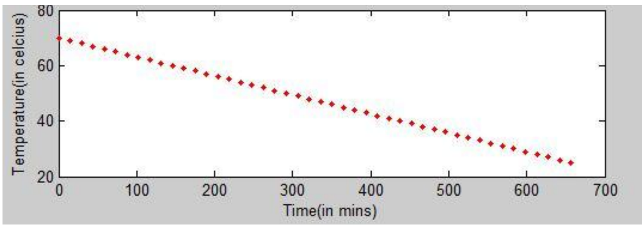
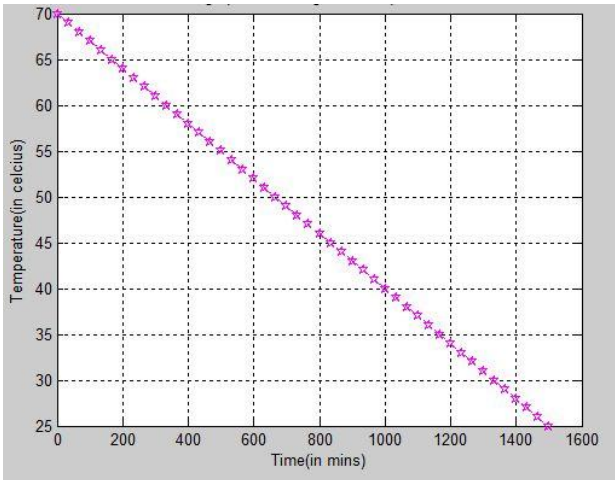


(e)

Figure 1. a) Temperature against Time for cellulose material, b) Temperature against Time for Mineral wool material, c) Temperature against Time for Polyurethane foam material, d) Temperature against Time for Straw bale, e) Temperature against Time for Fiberglass material

D. Results of Resistance of Heat through Polyurethane Foam

After modeling the container on COMSOL multiphysics and taking the ambient temperature of the outer materials to be 298K (25^{o}C) and the inner temperature to be 343K (70^{o}C), the result of the modeling is shown in figure 3.



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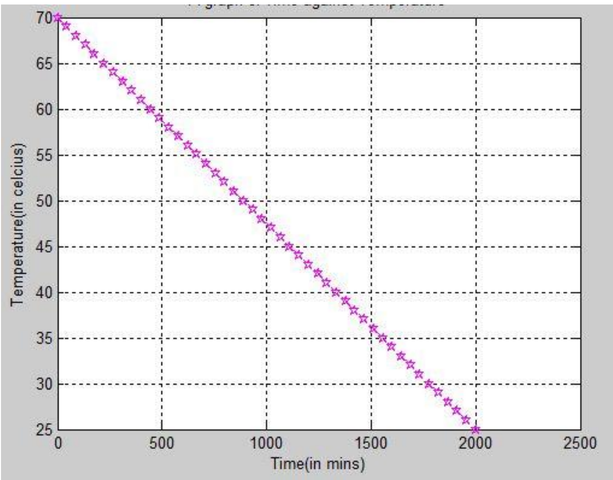
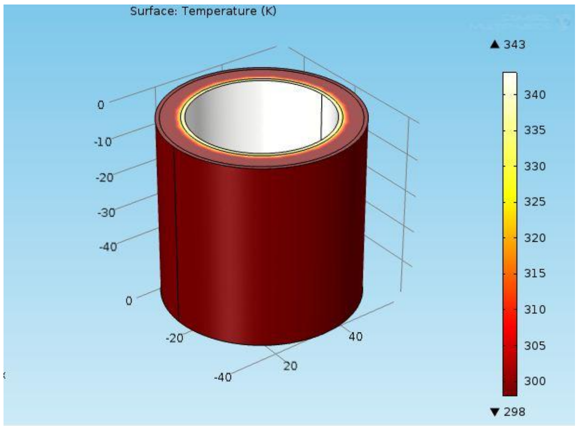


(b)

Figure 2. Time taken for temperature to reach room temperature for a) 15 mm and b) 20 mm polyurethane foam



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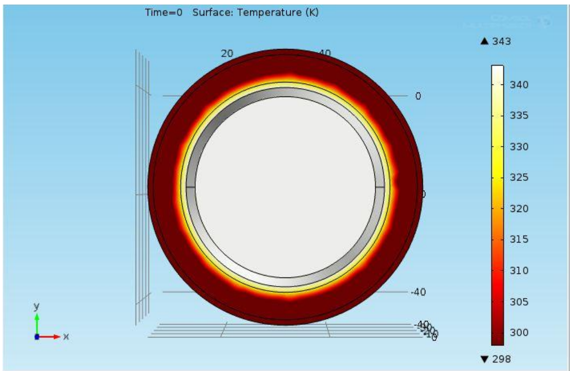


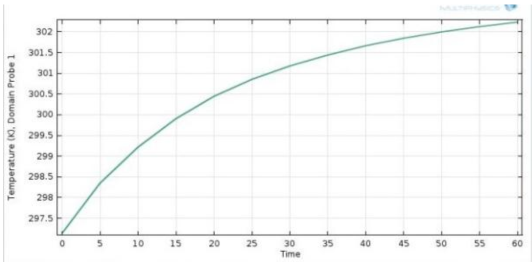
(b)

Figure 3. a) SW view of the 3D model result, b) Top view of the 3d model

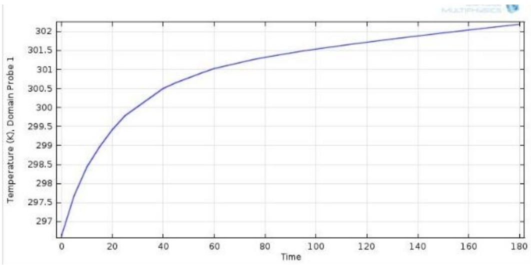
After the study of this thickness and using the governing equations the rate of heat loss, thermal resistance, temperature distribution and the rate of heat transfer was 10.92J, 1.4679 K/W, 212.526K/m and 171.3505W respectively. After which the thickness of the insulating material was increased to 20mm. Figure 3b, changing the temperature thickness to 20mm, the rate of heat loss, the heat transfer rate, thermal resistance and temperature distribution was 8.19J, 161.445W, 1.1542k/W, and 226.578K/m respectively. Comparing the result of the two thickness it was discovered that the higher the thickness of the material the lesser the heat lost in the container.

The rate at which polyurethane foam prevent heat loss with time for one hour, two hours and three hours was examined. The graph in fig. 4 shows the rate at which polyurethane prevents heat loss with time.

The graphs show how polyurethane foam prevent rate of heat loss. At 0 sec the temperature of the polyurethane was at room temperature but at one hour the temperature of the polyurethane foam increased to 301K, for two hours the temperature increased to 302K which also shows that polyurethane is favorable.



(a)



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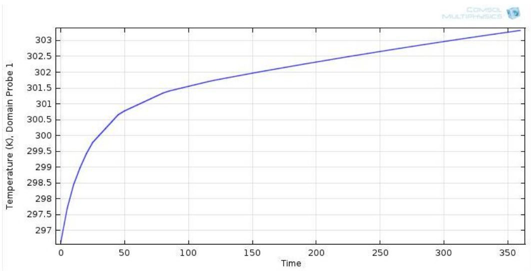

(c)

Figure 4. a) Time graph of heat loss in 60 mins, b) Time graph of heat loss in 180 mins, c) Time graph of heat in 360 mins

IV. CONCLUSION

A theoretical-physical model was developed to study the rate of heat transfer in a cylindrical hot water storage tank containing a water of temperature 70oC based on the governing equations of Fourier's law and newton's law of cooling. The model allows predicting of rate of heat loss, the global time variation of the temperature inside the container, the temperature distribution and the thermal resistance. This model was solved using the modified numerical code in MATLAB R2009b and COMSOL MULTIPHYSICS which is used to predict the way the heat is being lost in the container using different insulating material.

From this study it can be seen that it took cellulose 750 min, mineral wool 650 min, fiberglass 650 min, polyurethane foam 1250 min, straw bales 290 min before the water gets to room temperature using MATLAB to solve them. As the time increases the temperature of the water decreases in the tank and afterward the water maintains a steady temperature of the room temperature. From this it can be seen that polyurethane foam has the highest thermal resistance.

Using COMSOL MULTIPHYSICS it was found that at the 60 min there was sharp increase in the temperature and as the time increases polyurethane foam try to retain heat so as to reduce heat loss.

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