American Journal of Energy Engineering
2018; 6(2): 10-14
http://www.sciencepublishinggroup.com/j/ajee
doi: 10.11648/j.ajee.20180602.11
ISSN: 2329-1648 (Print); ISSN: 2329-163X (Online)

Home Appliances Efficiency Improvements for Energy Conservation in Debre Berhan City; Ethiopia

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To cite this article:
Mikias Hailu Kebede, Solomon Derbie Gont. Home Appliances Efficiency Improvements for Energy Conservation in Debre Berhan City; Ethiopia. *American Journal of Energy Engineering*. Vol. 6, No. 2, 2018, pp. 10-14. doi: 10.11648/j.ajee.20180602.11

Received: May 21, 2018; **Accepted**: June 19, 2018; **Published**: July 5, 2018

Abstract: This paper presents the analysis of efficiency improvements of home appliances such as Electrical Stove (Injera Mitad), Electrical Showers, Kerosene Stoves, Charcoal Stoves and Small Electrical Stoves for energy conservation. Most of the existing stoves have been manufactured by small facilities without any regard for energy efficiency standard and safety. It suffers from many shortfalls, such as, poor insulation, lack of temperature regulation, bulkiness and overall poor design that encourages wastage of heat. The energy efficiency of the ordinary electric stove is very low since much of the heat energy is lost through the bottom, its sides, on the top part of the oven and also due to the much delay in the existing Injera baking procedure. The overall efficiency of the electrical shower is affected by the reservoir efficiency and the characteristics of the pipe. Kerosene and charcoal stoves have high heat energy loss due to lack of insulation to their external cover. Therefore, the efficiency of those electrical home appliances can be improved by minimizing the losses through their covers and parts. This can be achieved by selecting appropriate low thermal conductivity materials and insulations.

Keywords: Home Appliances, Efficiency, Energy Conservation, Insulation, Thermal Conductivity, Simple Payback Period

1. Introduction

There are many home appliances in Debre Berhan city. However, most of them have low energy conversion efficiencies. Those home appliances use different energy sources, such as electricity, charcoal and kerosene. The electrical stove, Injera Mitad and electrical shower use the electrical energy to perform the required task. And also, there are stoves that use charcoal and kerosene.

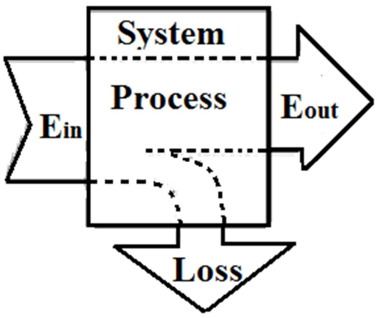

Figure 1. Representation of energy conversion.

Energy conversion efficiency is the ratio between the useful output of an energy conversion machine and the input, in energy terms. The useful output may be electric power, mechanical work, or heat. As we observe from Figure 1, the input energy (E_{in}) is equal to the sum of the output energy (E_{out}) and the losses.

$$\text{Device efficiency } (\eta) = \frac{\text{Useful Energy Output } (E_{out})}{\text{Energy Input } (E_{in})}$$

$$= \frac{\text{Output Power } (P_{out})}{\text{Input Power } (P_{in})} * 100\% \qquad (1)$$

Some of the home appliances considered in this study are given below in Table 1.

Table 1. Some of home appliances energy conversion processes.

Energy conversion device	Energy input	Useful energy output
Electrical stove (Injera Mitad)	Electrical	Thermal
Electrical stoves	Electrical	Thermal
Electrical shower	Electrical	Thermal
Kerosene cooking stove	Chemical	Thermal

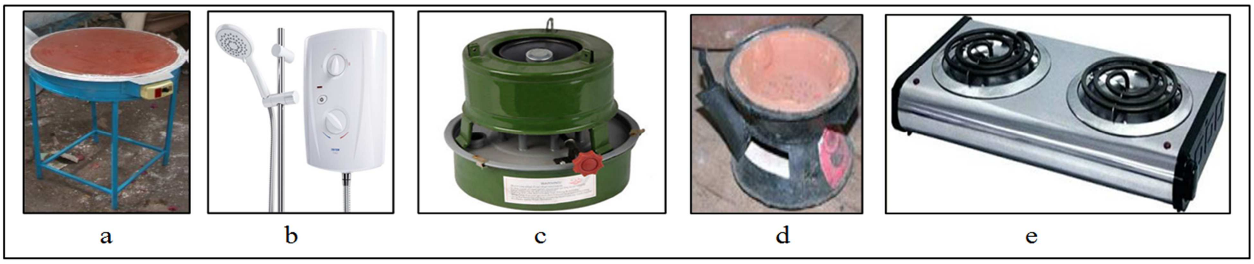

Figure 2. *a: Electrical Stove (Injera Mitad) , b: Electrialc Shower , c : Kerosene Stove, d: Charcoal Stove, e : Small Electrical Stove.*

Electrical Stove (Injera Mitad) is used for the preparation of the Ethiopian staple food Injera. Electric Injera baking Mitad consumes large quantity of electricity. Most of the existing stoves have been manufactured by small facilities without any regard for energy efficiency standard and safety. It suffers from many shortfalls, such as, poor insulation; lack of temperature regulation, bulkiness and overall poor design that encourages wastage of heat. The energy efficiency of the ordinary electric stove is very low since much of the heat energy is lost through the bottom, its sides, on the top part of the oven and also due to the much delay in the existing Injera baking procedure. Therefore, the efficiency of the electrical stove is improved by minimizing the losses through its cover and the losses through its bottom. Traditionally, the Injera is baked on a 15 mm thick and 57 cm diameter clay plate, called Mitad. The women use these stove an average of 2 hours per session of preparing Injera. During this time there is high electric consumption, resulting from the low energy efficiency of the electrical stoves [1, 10].

Electric showers work in much the same way as other electric appliances that get hot, including electric toasters and hair dryers. They send an electric current through a piece of metal called a heating element. This has a moderately high resistance, so it gets really hot when electricity moves through it. Cold water flows past the element, picking up heat and heading out through the nozzle where you are standing [9, 11].

With millions of people below the poverty line in the developing countries, using kerosene for their daily cooking and lighting purposes, and kerosene being a fossil fuel, with all the attendant problems such as procurement, affordability and indoor air pollution. These problems should be solved for good quality of life. However, the main objective of this study here is analyzing the energy efficiency of kerosene stoves [2, 8, 16].

Charcoal is second only to wood as a Third World fuel. Burning wood to make charcoal wastes energy and causes pollution, and most Third World charcoal production is inefficient. Like firewood, the demand for charcoal is growing, and cannot be stopped. Again, there are large savings to be made with more efficient cooking stoves, and also by improving the efficiency of charcoal production [6].

2. Efficiency Improvement Analysis

2.1. Heat Transmission Modes

Heat is transferred by conduction, convection or radiation, or by a combination of all three. Heat always moves from warmer to colder areas; it seeks a balance. If the interior of an insulated fish hold is colder than the outside air, the fish hold draws heat from the outside. The greater the temperature difference, the faster the heat flows to the colder area [3, 6].

2.1.1. Conduction

By this mode, heat energy is passed through a solid, liquid or gas from molecule to molecule in a material. In order for the heat to be conducted, there should be physical contact between particles and some temperature difference. Therefore, thermal conductivity is the measure of the speed of heat flow passed from particle to particle. The rate of heat flow through a specific material will be influenced by the difference of temperature and by its thermal conductivity.

2.1.2. Convection

By this mode, heat is transferred when a heated air/gas or liquid moves from one place to another, carrying its heat with it. The rate of heat flow will depend on the temperature of the moving gas or liquid and on its rate of flow.

2.1.3. Radiation

Heat energy is transmitted in the form of light, as infrared radiation or another form of electromagnetic waves. This energy emanates from a hot body and can travel freely only through completely transparent media. The atmosphere, glass and translucent materials pass a significant amount of radiant heat, which can be absorbed when it falls on a surface. (Example: the ship's deck surface on a sunny day absorbs radiant heat and becomes hot). It is a well-known fact that light-colored or shiny surfaces reflect more radiant heat than black or dark surfaces; therefore the former will be heated more slowly.

2.1.4. Specific Heat Capacity

Specific heat capacity is the amount of heat per unit mass required to raise the temperature by one degree Celsius. The relationship between heat and temperature change is usually expressed in the form in equation (2) where C is the specific heat. The relationship does not apply if a phase change is encountered, because the heat added or removed during a phase change does not change the temperature [5, 10, 14].

$$\text{Heat added} = \text{specific heat} * \text{mass} * (T_{final} - T_{initial})$$

$$Q = Cm\Delta T = Cm(T_f - T_i) \tag{2}$$

Where:
Q = amount of heat energy gained or lost by substance
m = mass of sample
C = specific heat capacity (J °C $^{-1}$ g^{-1} or J K^{-1} g^{-1})
T_f = final temperature
T_i = initial temperature

2.2. Thermal Properties of Insulating Materials

The thermal properties of insulating materials and other common fishing vessel construction materials are known or can be accurately measured. The amount of heat transmission (flow) through any combination of materials can be calculated. However, it is necessary to know and understand certain technical terms to be able to calculate heat losses and understand the factors that are involved [6]. By convention, the ending "-ity" means the property of a material, regardless of its thickness and the ending "–ance" refers to the property of a specific body of given thickness.

2.2.1. Heat Energy

One kilocalorie (1 kcal or 1000 calories) is the amount of heat (energy) needed to raise the temperature of one kg of water by one degree Celsius (°C). The SI standard unit for energy is Joule (J). One kcal is approximately 4.18 kJ (this varies slightly with temperature). Another unit is the Btu (British thermal unit). One Btu corresponds roughly to 1 kJ.

2.2.2. Thermal Conductivity

In simple terms this is a measure of the capacity of a material to conduct heat through its mass. Different insulating materials and other types of material have specific thermal conductivity values that can be used to measure their insulating effectiveness. It can be defined as the amount of heat/energy (expressed in kcal, Btu or J) that can be conducted in unit time through unit area of unit thickness of material, when there is a unit temperature difference. Thermal conductivity can be expressed in kcal m^{-1} °C^{-1}, Btu ft^{-1} °F^{-1} and in the SI system in watt (W) m^{-1} °C^{-1}. Thermal conductivity is also known as the k-value.

2.2.3. Coefficient of Thermal Conductance

The Coefficient of thermal conductance is designated as λ (the Greek letter lambda) (in (kcal m^{-2} h^{-1} °C^{-1}) and defined as the amount of heat (in kcal) conducted in one hour through 1 m^2 of material, with a thickness of 1 m, when the temperature drop through the material under conditions of steady heat flow is 1 °C. The thermal conductance is established by tests and is the basic rating for any material. λ can also be expressed in Btu ft^{-2} h^{-1} °F^{-1} (British thermal unit per square foot, hour, and degree Fahrenheit) or in W m^{-2}K^{-1}.

2.2.4. Thermal Resistivity

The thermal resistivity is the reciprocal of the k-value (1/k).

2.2.5. Thermal Resistance (R-value)

The thermal resistance (R-value) is the reciprocal of λ (1/λ) and is used for calculating the thermal resistance of any material or composite material. The R-value can be defined in simple terms as the resistance that any specific material offers to the heat flow. A good insulation material will have a high R-value. For thicknesses other than 1 m, the R-value increases in direct proportion to the increase in thickness of the insulation material. This is x/λ, where x stands for the thickness of the material in meters.

2.2.6. Coefficient of Heat Transmission

The symbol U designates the overall coefficient of heat transmission (in kcal m^{-2} h^{-1} °C^{-1}) for any section of a material or a composite of materials. The SI units for U are kcal per square meter of section per hour per degree Celsius, the difference between inside air temperature and outside air temperature. It can also be expressed in other unit systems. The U coefficient includes the thermal resistances of both surfaces of walls or flooring, as well as the thermal resistance of individual layers and air.

2.3. Overall Heat Transfer Coefficient

The overall heat transfer coefficient, or U-value, refers to how well heat is conducted over a series of mediums. Its units are the W / (m^2 °C) [Btu/ (hr-ft^2 °F)].

The overall heat transfer coefficient is influenced by the thickness and thermal conductivity of the mediums through which heat is transferred. The larger the coefficient, the easier heat is transferred from its source to the product being heated. In a heat exchanger, the relationship between the overall heat transfer coefficient (U) and the heat transfer rate (Q) can be demonstrated by using equation 3 [3, 4, 15].

$$Q=U*A*(\Delta T) \quad (3)$$

Where:
Q = heat transfer rate, W=J/s [btu/hr]
A = heat transfer surface area, m^2 [ft^2]
U= overall heat transfer coefficient, W/(m^2°C[Btu/(hr-ft^2°F)]
ΔT = Temperature difference, °C [°F]

From this equation we can see that the U value is directly proportional to Q, the heat transfer rate. Assuming the heat transfer surface and temperature difference remain unchanged, the greater the U value, the greater the heat transfer rate. In other words, this means that for a same kettle and product, a higher U value could lead to shorter batch times.

Several equations can be used to determine the U value, one of which is given in equation 4 [4]:

$$\frac{1}{U}=\frac{1}{h_1}+\frac{L}{\lambda}+\frac{1}{h_2} \quad (4)$$

Where:
h_1 and h_2 = convective heat transfer coefficients, W/(m^2 °C)
L= thickness of the wall, m
λ = thermal conductivity, W/ (m°C)

2.4. Radiation Heat Transfer

Heat transfer due to emission of electromagnetic waves is known as thermal radiation.

Heat transfer through radiation takes place in form of electromagnetic waves mainly in the infrared region. Radiation emitted by a body is a consequence of thermal agitation of its composing molecules. Radiation heat transfer can be described by a reference to the so-called 'black body' [7, 12, 13].

A black body is defined as a body that absorbs all radiation that falls on its surface. Actual black bodies do not exist in nature - though its characteristics are approximated by a hole in a box filled with highly absorptive material. The emission spectrum of such a black body was first fully described by Max Planck.

A black body is a hypothetic body that completely absorbs all wavelengths of thermal radiation incident on it. Such bodies do not reflect light, and therefore appear black if their temperatures are low enough so as not to be self-luminous. All blackbodies heated to a given temperature emit thermal radiation.

The radiation energy per unit time from a blackbody is proportional to the fourth power of the absolute temperature and can be expressed with Stefan-Boltzmann laws [1, 2]:

$$q=\sigma T^4 A \quad (5)$$

Where:

q= heat transfer per unit time (W)

σ= 5.6703 10^{-8} (W/m^2K^4) – The Stefan-Boltzmann constant

T= absolute temperature Kelvin (K)

A= area of the emitting body (m^2)

2.4.1. Gray Bodies and Emissivity Coefficients

For objects other than ideal blackbodies ('gray bodies') the Stefan-Boltzmann law can be expressed as [7]:

$$q=\varepsilon\sigma T^4 A \quad (6)$$

Where:

ε = emissivity of the object (one for a black body)

For the gray body the incident radiation (also called irradiation) is partly reflected, absorbed or transmitted.

2.4.2. Net Radiation Loss Rate

If a hot object is radiating energy to its cooler surroundings the net radiation heat loss rate can be expressed as:

$$q=\varepsilon\sigma \left(T_h^4-T_c^4\right) A_c \quad (7)$$

Where:

Th = hot body absolute temperature (K), Tc = cold body absolute temperature (K), Ac = area of the object (m2).

2.5. Pipe Heat Loss Calculation

Considerable amounts of heat energy can be lost through poorly insulated pipe work in Electrical Showers. It is therefore important to ensure that hot water and steam pipe work is properly insulated. A range of insulating materials is available and these can be inorganic, based on crystalline or amorphous silicon, aluminum or calcium, or organic, based on hydrocarbon polymers in the form of thermosetting/thermoplastic resins or rubbers. They can be either flexible or rigid, both types being available in preformed pipe sections.

Once the overall resistance of the pipe work is determined, the total heat loss per meter run can be calculated by dividing the temperature difference between the fluid and ambient air by the total resistance [6, 8, 9]:

$$Q=\frac{\Delta T}{R_t} \quad (8)$$

Where: R_t is the total thermal resistance of pipe work per unit length (mK/W), ΔT is the temperature difference between the surface and the bulk fluid (°C).

The internal and external surface resistance per unit length of a pipe can be expressed as [6, 8, 9]:

$$R_{so} \text{ or } R_{si}=\frac{1}{h*A} \quad (9)$$

Where:

h = the surface heat-transfer coefficient (W/m^2K),

A = the surface area (m^2).

If the pipe has cylindrical shape, the thermal resistance of pipe wall per unit length (mK/W), Rw:

$$R_w=\frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi\lambda} \quad (10)$$

Where:

r_1 = internal radius, r_2 = external radius, λ = thermal conductivity

Area of the pipe = A=2πrL, L is the length of the pipe and r is the internal radius of the pipe (D/2; where, D=Diameter)

The overall resistance per unit length of a typical insulated pipe can therefore be represented by [6]:

$$R_t= R_{si} + R_w + R_{so} + R_{ins} + R_{ext} \quad (11)$$

Where:

Rt = the total thermal resistance of pipe work per unit length (mK/ W), Rw = the thermal resistance of pipe wall per unit length (mK/ W), Rins = the thermal resistance of insulation per unit length (mK/W), Rext = the thermal resistance of the external cover per unit length (mK/W), and Rsi and Rso are the internal and external surface thermal resistances of insulation per unit length (mK/W).

3. Result and Discussion

The results of this study are shown in Table 2 and 3. Table 2 shows the results of the energy conserved (kWh/year) and the amount of saved money (in Ethiopian Birr (ETB) per year) by improving the efficiencies of each home appliance. For instance, the energy saved by improved electrical stove (Injera Mitad) is 128.95 kWh per year while the money saved is 64.5 Birr per year, the energy saved by improved electrical shower is 266.91 kWh per year while the money saved is 133.46 Birr per year, the energy saved by improved kerosene stove is 139.37 kWh per year while the money saved is 189.82 Birr per year, the energy saved by improved charcoal stove is 75.75 kWh per year while the money saved is 141.54 Birr per year, and the energy saved by improved small electrical stove is 306.5 kWh per year while the money saved is 153.25 Birr per year.

The comparison of home appliances efficiency is illustrated in two categories, which are previous and improved efficiency values, as shown in Table 3. It indicates the comparison of both the previous value and improved value. Therefore, the efficiency for electrical stove (Injera Mitad) is improved from 35 to 40.1, for electrical shower from 90 to 98.8, for kerosene stove from 55 to 59.54, for charcoal stove from 35 to 36.66, and the efficiency for small electrical stove is improved from 60 to 76. The simple payback period (in years) of each home appliance is also included.

Table 2. *Energy conservation results.*

Home Appliance	Quantity	Input Power (kW)	Energy Saved (kWh/year)	Money Saved (Birr/year)
Electrical Stove (Injera Mitad)	1	3.5	128.95	64.5
Electrical Showers	1	2.5	266.91	133.46
Kerosene stoves	1	1.67	139.37	189.82
Charcoal Stoves	1	1.53	75.75	141.54
Small Electrical Stoves	1	2.0	306.5	153.25

Table 3. *Summary of efficiency improvements.*

Home Appliance	Previous Efficiency (%)	Improved Efficiency (%)	Simple Payback Period (SPP) (Year)
Electrical Stove (Injera Mitad)	35	40.1	1.55
Electrical Showers	90	98.8	1.8
Kerosene stoves	55	59.54	0.26
Charcoal Stoves	35	36.66	0.92
Small Electrical Stoves	60	76	0.52

4. Conclusion

From the overall improvements of the home appliances efficiency, it is concluded that there is a good possibility to save large amount of electrical energy and chemical energy. This saved energy can be used for different purposes.

Since the research is done by considering low cot material, the implantation of the research will not be difficult. Therefore, the research can support the technicians of the electrical stoves, kerosene stoves and charcoal stoves to consider the energy efficiency of the home appliances.

This research could contribute a lot as an input for the development of energy efficient home appliances for energy conservation. And also, it helps as an input for further improvement of the appliances efficiency.

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