FEDERAL UNIVERSITY OYE-EKITI

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TITLED:

RENEWABLE ENERGY AND NATURAL REFRIGERANTS: THE VERITABLE TOOLS FOR SOLVING THE MAJOR ENVIRONMENTAL PROBLEMS

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Renewable Energy and Natural Refrigerants: The Veritable Tools for Solving the Major Global Environmental Problems

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PREAMBLE

Mr. Vice-Chancellor Sir, this is the day the Lord has made, I will rejoice and be glad in it (Psalms 118:24). I want to express my profound gratitude to God Almighty, the Omnipotent, the Omniscience, the I am that I am, the Alpha and Omega who has kept me alive to see this day. I feel highly honoured, privileged, and delighted to be called to give the 9th Inaugural Lecture of the Federal University Oye-Ekiti, Ekiti State, Nigeria; the second from the Faculty of Engineering and the first from Department of Mechanical Engineering.

An Inaugural Lecture is an academic exercise to specifically mark the inauguration or installation of a University Professor at a ceremonial occasion. It symbolizes a significant milestone in any academic career. It is an academic responsibility for all Professors in the course of their academic career in the University. This is a privilege to present an overview of one’s field of specialization, explain what has been done and justify one's contributions to knowledge and its relevance to humanity.

My field of specialization or area of research was ordered by God, who showed me how humanity has been blinded by its need for energy and not see the havoc this quest is creating on the earth's ecosystem. The consequential fuel depletions and climate changes have forced humanity to an energy crisis. This has revealed the urgency for seeking alternative sources to quench the ever growing demand for energy. Mr Vice-Chancellor Sir, distinguished colleagues, ladies and gentlemen, I stand before you therefore, to present my Inaugural Lecture, titled:

"Renewable Energy and Natural Refrigerants: the Veritable Tools for Solving the Major Global Environmental Problems".

1. INTRODUCTION

The energy system is presently facing various challenges, most especially high consumption levels, inadequate energy availability and environmental concerns such as air pollution, ozone depletion, global warming and climate change (Oni and Bolaji, 2011). Energy can generally be classified into two: renewable and non-renewable. Non-renewable energy sources are not capable of being replenished or are replenished slowly. These include: nuclear fuels (such as uranium) and fossil fuels (such as coal, petroleum and natural gas). Renewable energy sources are those that are naturally replaced in an unceasing manner. They are also called Clean Energy, or Green Energy, as they do not discharge carbon dioxide (CO_2) or other greenhouse gases. These include: solar, wind and water, which are inexhaustible and also other forms of organic materials that can be converted into gaseous or liquid fuels by thermo-chemical or biological processes (Bolaji, 2003; Bolaji, 2005a; Vuuren *et al*., 2012).

The conventional sources of energy are all commonly non-renewable sources of energy. Their high consumption rate has caused their known reserves to be depleted rapidly (Bolaji, 1997).The increased dependence on non-renewable energy has a lot of negative consequences on both people and environment. Energy systems, since modern history, have been central to economic development and social progress, but its productions, transportation and uses cause a wide range of major environmental problems at the local, national and global levels (Bolaji, 2005b). Due to the persistent rise in demand for energy, energy systems developed thus far to meet this increasing demand are obviously unsustainable, as they result directly or indirectly in health problems, pollution, acidification of ecosystems, land and water contamination, loss of bio-diversity, ozone layer depletion and global warming (Bolaji and Adejuyigbe, 2006).

Global greenhouse gas emissions have increased greatly in recent decades, which have resulted in global climate change and environmental damage. The significant portion of this growth in emissions and associated global warming is produced by human activity. It is absolutely necessary to drastically reduce pollution and the emission of greenhouse gases. One of the most veritable tools to combat these global environmental problems is the worldwide applications of environmentally friendly energy (renewable energy) (Bolaji and Onipede, 2005a and 2005b; Oyelaran *et al*., 2014).

1.1 Importance of Energy

What is energy? Energy is the measures of the ability of an object or system to do work on another system or object. It comes in multiple forms: kinetic, potential, thermal (heat), chemical, electromagnetic, and nuclear energy. Energy is a vital and important part of most aspects of daily life. It is the life blood of the modern world. The worth of life, and even its nourishment, depends on the availability of energy (Bolaji, 2012a). The provision of basic needs such as transport, cooking, heating, cooling, lighting, essential health care, educational aids, communication and use of appliances depend critically on availability of energy. The per capita energy consumption of a country is one of the development indicators that can be used to assess the standard of living of that country. Equally, inadequate access to energy will contribute to poverty and economic decline (Akinola and Bolaji, 2006).

According to Vuuren *et al*. (2012), development of the energy system is of critical importance for achieving major societal objectives, such as sustainable economic development and achieving the millennium development goals, and avoiding disastrous climate change. The importance of energy in a sustained economic development is recognised universally, and historical data confirm that there is a strong connection between the accessibility of energy and economic activity. Energy has always been an indispensable input to all aspects of the modern social life; it is the life-wire of industrial production; it is indeed an important factor in all the sectors of any country. It plays the most central role in the economic growth, progress and development of a Nation. It fuels productive activities including agriculture, commerce, manufacturing, industry and mining (Adegoke and Bolaji, 1999). Uninterrupted energy supply is a vital issue for all countries. It is considered a prime agent in the generation of wealth and a significant factor in economic development.

1.2 Primary and Secondary Sources of Energy

Over the centuries, man has harnessed different types of energy in order to meet the basic essentials of life. For example, the early man created fire through the friction of two stones to burn something to provide light and heat. Throughout history, man has discovered other energy resources such as sun, wind, ocean, coal, gas and oil (Bolaji and Olalusi, 2009; Ullah *et al*., 2013). Sources of energy can be grouped into primary and secondary sources (Figure 1). Energy extracted or taken directly from the environment is referred to as ***primary energy***. Types of primary energy are (Bolaji, 2005c):

(i) Non-renewable energy such as crude oil, natural gas, coal and nuclear fuel.

(ii) Renewable energy includes solar, wind, geothermal, hydropower, biomass and ocean energy.

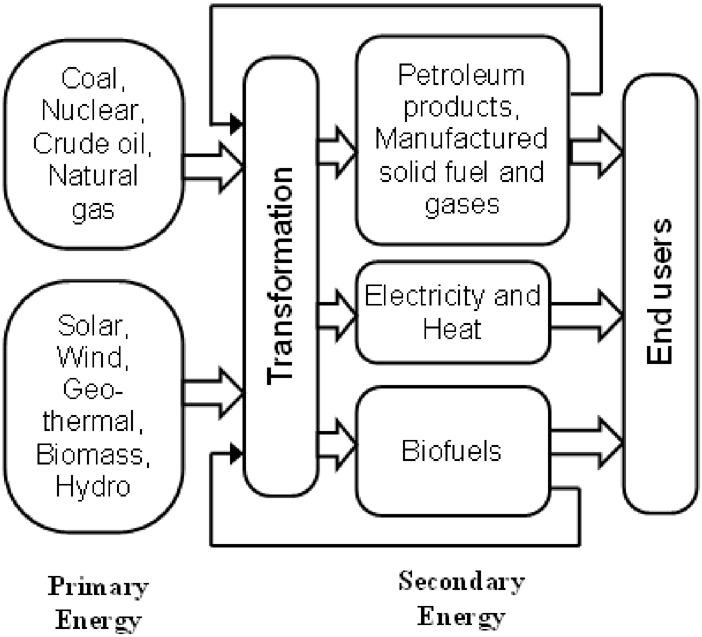


Figure 1. Primary and secondary sources energy.
(Source: Bolaji, 2005c)

Petroleum, coal, and natural gas constitute about 85% of the world's primary energy consumption (UNEP, 2009; EIA, 2010). ***Secondary energy*** is converted from the primary energy in the form of electricity or fuel, such as gasoline, fuel oil, methanol, ethanol, and hydrogen (Bolaji, 2005c). The primary energy of renewable energy sources, such as solar, wind, biomass, geothermal and hydro is usually equated with either electrical or thermal energy produced from them. The final energy is either in form of electrical, thermal, mechanical or chemical energy, which is referred to as useful energy (Capehart, 2007; EIA, 2011). Non-renewable energy sources or fossil fuels contain high percentages of carbon and include mainly coal, petroleum and natural gas. Natural gas, for example, contains only very low boiling point and gaseous components, while gasoline contains much higher boiling point components.

1.3 Energy and Environmental Problems

In the early seventies of the last century, after the oil crises, the concern was on the cost of energy. During the past four decades, the risk and reality of environmental degradation have become more apparent. It has been seen that the consumption of non-renewable sources of energy most especially fossil fuels has caused more environmental damage than any other human activity (Bolaji and Adu, 2007). The growing evidence of environmental problems is due to a combination of several factors, since the environmental impact of human activities has grown dramatically. This is due to the increase of the world population, energy consumption and industrial activities (Bolaji, 2005d; Bolaji, 2006a).

Currently, non-renewable energy sources (fossil fuels) provide the bulk of the world's primary sources of energy (Aiyedun *et al*., 2008). However, concern grows daily over the negative impacts fossil fuels have on the environment. Electricity generated from fossil fuels such as coal and crude oil is the major human activity that has led to many problems being faced today such as ozone depletion and global warming. Electricity generation provides about one half of the world carbon dioxide emissions. Electricity generation through coal-firing gives rise to twice as much carbon dioxide as natural gas per unit of power at the point of use. Substitution of coal by natural gas requires consideration of methane leakage, and 3% leakage means that the global warming potential from using gas is the same as burning coal in developed countries, with average 33 % thermal efficiency. The difference is greater considering the developing countries' average efficiency of 25 % (Demirel, 2012). The greenhouse gas emissions from electricity generation using various sources of fuels are shown in Figure 2. However, hydro energy and most renewable energy sources do not directly emit any carbon dioxide.

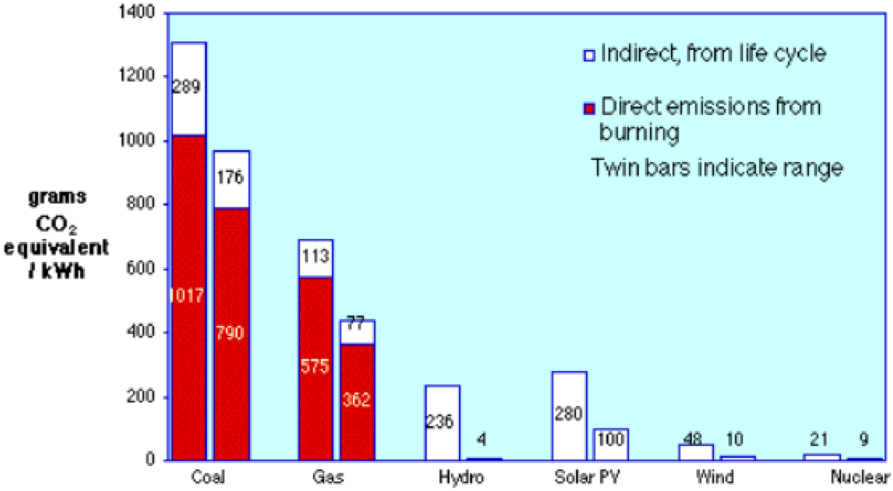


Figure 2: Greenhouse gas emissions from electricity generation (Source: Spadaro et al., 2000)

About 21.3 Giga-tons of carbon dioxide are produced from the burning of fossil fuels per year. Natural processes usually absorb about half of this amount, while the remaining half (10.65 billion tons) is added to the atmospheric carbon dioxide per year (Jacobson, 2009). Table 1 shows typical emission of carbon dioxide from the combustion of various fuels

A tonne of carbon is the same as:

$$\frac{M_{CO_2}}{M_C} = \frac{44}{12} = 3.7\,tons \text{ of carbon dioxide} \qquad (1)$$

Where, M_{CO2} = molar mass of carbon dioxide (kg)
M_C = molar mass of carbon (kg)

Carbon dioxide emission can be calculated as

$$e_{CO_2} = \left[\frac{C_f}{E_f}\right]\left[\frac{MW_{CO_2}}{MW_C}\right] \qquad (2)$$

Where, e_{CO2} = CO_2 emission (kg/kWh),
C_f = carbon content in the fuel (kg/kg fuel), and
E_f = energy content of the fuel (kWh/kg fuel).

Table 1: CO_2 Emission from the combustion of various fuels

Fuel	**Specific CO_2 emission (kg/kWh)**
Coal (bituminous/anthracite)	0.37
Gasoline	0.27
Light oil	0.26
Diesel	0.24
Liquefied Petroleum Gas (LPG)	0.24
Natural gas (methane)	0.23
Crude oil	0.26
Kerosene	0.26
Biofuel (Wood and Peat)	0.39
Lignite	0.36

(Source: Demirel, 2012)

1.4 Effects of Global Warming and Climate Change

It has been widely accepted that the excessive fossil fuel consumption will not only increase the rate of reduction in fossil fuel reserves, but will also have a significant negative impact on the environment, resulting in increased health risks and the threat of global climate change. There is strong scientific evidence that the average temperature of the earth's surface is rising. This is a result of the increased concentration of carbon dioxide (CO_2), and other greenhouse gases (GHGs) in the atmosphere as released by burning fossil fuels (Oyelaran *et al*., 2015a). Global warming will eventually cause significant changes in the climate, which will have a significant effect on both human existence and the ecosystem. (Ismaila *et al*., 2012; Samuel *et al*., 2013).The change of Earth's climate will possibly cause havoc for the growing seasons, the amount of rainfall needed for crops, the rising level of the oceans, and the endangerment of many coastal cities throughout the world, and other problems.

According to rankings from three top US and British climate research centres, the ten hottest years on record have all occurred since 1998 and nine of the ten hottest years on record, as shown in Table 2, occurred in the last decade. The global annual 'mean surface temperature' used for these rankings is calculated from a historical record drawn from roughly

7000 stations. The record from the fourth climate research centre, Japanese Meteorological Agency (JMA), is in agreement with the other three centres. A high degree of agreement year by year occurs in spite of the different methodologies used (JMA, 2011; UNEP, 2011). Figure 3 shows the Global average temperature anomaly over the past 130 years modelled from station temperature data. Twelve (12) of the thirteen (13) warmest years occurred in 1995 to 2007. Only 1996 year was not among them and 1998 was the warmest year with an anomaly of +0.58 ^{o}C (Calm, 2008).

Table 2: Ten world hottest years as of 2011 with nine them occurred within the preceding decade

	Climate Research Centres					
	NASA Goddard Institute for Space Studies		**NOAA National Climate Data Centre**		**Hadley Centre Meteorological Office UK**	
Rank	**Year**	**Anomaly**	**Year**	**Anomaly**	**Year**	**Anomaly**
1st	2010	0.56	2010	0.52	1998	0.52
2nd	2005	0.55	2005	0.52	2010	0.50
3rd	2007	0.51	1998	0.50	2005	0.47
4th	2009	0.50	2003	0.49	2003	0.46
5th	2002	0.49	2002	0.48	2002	0.46
6th	1998	0.49	2006	0.46	2009	0.44
7th	2006	0.48	2009	0.46	2004	0.43
8th	2003	0.48	2007	0.45	2006	0.43
9th	2004	0.41	2004	0.45	2007	0.40
10th	2001	0.40	2001	0.42	2001	0.40

**Anomaly: Temperature above long-time average (^{o}C)*

(Sources: UNEP, 2011; JMA, 2011)

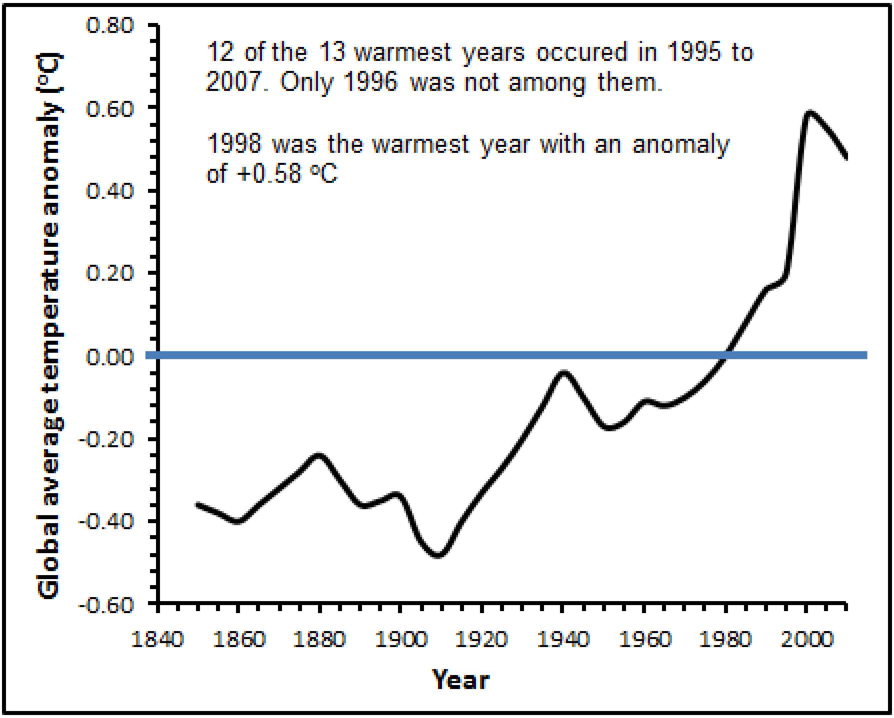


Figure 3: Global average temperature anomaly over the past 130 years (Source: Calm, 2008)

Climate change will cause certain areas of the world that had produced sufficient food to produce less food, leading to malnutrition and hunger. For example, scientific evidence now suggests that the spewing of sulphur dioxide in the air by industries from the United States, Canada, Europe and Asia caused the decrease in rainfall in Africa, creating malnutrition and food shortage (Verrengia, 2002; Crone, 2010). This situation will not only create food shortage in certain areas of the world, but will also encourage more people from these areas migrating to better regions where they will be properly fed. Therefore, in the world today, there is a growing awareness of the need to tap from God given renewable sources of energy as viable alternative and solution to the negative environmental impacts of fossil fuels.

2. RENEWABLE ENERGY AND SUSTAINABLE DEVELOPMENT

Most of the world's energy is currently produced and consumed in ways that cannot be sustained. There is an intimate connection between energy, the environment and sustainable development. A society seeking sustainable development ideally must utilize only energy resources which cause no environmental impact (Oyelaran *et al*., 2015b, Waheed *et al*., 2015). The issue of sustainable development is gaining steady momentum. The renewable energies being inherent, sustainable and environmentally friendly are gaining popularity.

2.1 Renewable Energy

Renewable energy sources such as solar, wind, geothermal, biomass and hydropower, are environmentally friendly and are healthier energy for use in attaining technological development under a sustainable environment, both in the developed and the developing countries (Bolaji and Adu, 2007). These sources of energy can never be exhausted; they are replenished more rapidly, therefore they are known as "*renewable energy*". They cause less emission and are available locally. Widely use of renewable energy can, to a large extent, decrease chemical, radioactive and thermal pollution. They stand out as viable sources of clean and limitless energy. These are also known as non-conventional sources of energy.

Renewable energy technologies yield profitable energy by transforming natural occurrences into useful forms of energy. In its several forms, renewable energy originates directly from the sun, or from heat generated deep within the earth (geothermal). These resources have huge energy potential, but with difficult technical and economic challenges to be confronted before they can be significantly harnessed. Renewable energy resources are usually diffused and not completely accessible, and most of them are intermittent and have individual regional variability (Bolaji *et al*., 2008; Bolaji and Olalusi, 2008). These are areas of research focus for development of renewable energy technologies.

The global energy consumption data in 2008 shows that about 19% of the total consumption derived from renewable energy sources, with 13% of it coming from biomass, which is mainly used for heating. Hydroelectricity contributed 3.2%, while the remaining 2.8 % were generated from other renewable sources such as wind, solar, geothermal and biofuels (Table 3). About 18 % of the global electricity generation is obtained from renewable energy sources (Table 4), with hydroelectricity contributing 15% and 3% from other renewable energy (EIA, 2011).

Table 3: Renewable energy's contributions to global energy consumption in 2008

Type of renewable energy	Percentage contribution
Biomass	13.0 %
Hydroelectricity	3.2 %
Other renewable sources (e.g. wind, solar, geothermal and biofuels)	2.8 %
Total	**19.0 %**

(Source: EIA, 2011)

Table 4: Renewable energy's contributions to global electricity generation in 2008

Type of renewable energy	Percentage contribution
Hydroelectricity	15.0 %
Other renewable sources (e.g. biomass, wind, solar, geothermal and biofuels)	3.0 %
Total	**18.0 %**

(Source: EIA, 2011)

Nowadays, significant progress is made by improving the collection and conversion efficiencies, lowering the initial and maintenance costs and increasing the reliability and applicability of renewable energy technologies (Oyelaran *et al*., 2015c). These developments coupled with the issues of climate change concerns and high oil prices will lead to increase in renewable energy usage (Bolaji and Bolaji, 2010). Many countries now consider solar, wind and other renewable energy technologies as the key to a clean energy future. The UK Government, in

February 2008, established a review of current and future targets to reduce the UK's CO_2 emissions. The new climate change bill (DEFRA, 2008) set a target reduction of at least 60% by 2050. Conventional fuels could be replaced with Renewable energy in the areas of transport fuels, power generation, hot water, rural electrification, cooling and space heating (Adejuyigbe *et al*., 2013). Worldwide, research and development in the field of renewable energy resources and systems have been conducted during the last two decades. Energy conversion systems that are based on renewable energy technologies appear to be cost effective compared to the projected high cost of fossil fuels.

2.2 Sustainable Energy

Sustainable energy is the energy that meets the needs of the present without compromising the ability of future generations to meet their own needs. It is required that a sustainable supply of energy and efficient utilization of energy resources be secured. Such a supply in the long term should be readily available at reasonable cost, be maintainable, ecological and be able to be utilized for all the required tasks without causing negative societal impacts. This is why there is a close connection between renewable sources of energy and sustainable energy. Non-renewable energy sources are polluting and expensive, and because of their local, regional and global negative impacts, they are unacceptable sources of power for sustainable development. Low and Zero Carbon Technologies (LZCT) or renewable technologies have the prospect to meet the important concern with respect to economical, ecological and social issues of sustainable development (Bolaji and Abiala, 2012).

Sustainable energy development involves deliberate and conscious efforts to make energy accessible for the public at a reasonable cost for the present-day and future generation. It is an attempt capable of meeting the energy needs or requirement of individual and corporate establishment simultaneously, not only for the present, but also for that of the future. Sustainable energy will speed up the provision of modern energy for electrification and powering other basic social economic activities in the urban and rural areas, and at the same time fight climate change (Bolaji and Adu, 2007).

The bulk of the power generated all over the world is used in the urban areas because the majority of the rural areas, most especially in developing countries, are not connected to the grid. Rural societies do not actually need a huge amount of electricity, because, there is little or no industrial activity there. Nevertheless, they are in dire need of modern energy for domestic activities and basic socio-economic such as heating, lighting, small entrepreneurships and small scale businesses (Adu and Bolaji, 2004). On account of this background, fossil fuels are not the solution to the energy needs of rural areas but sustainable energy systems, based on renewable energy resources which are capable of delivering the socio-economic services in the rural areas with wide range of opportunities to protect the environment and create economic growth. Renewable energy systems represent an excellent opportunity to offer a higher standard of living to local people. They would also make a substantial input towards poverty alleviation in terms of improving the overall welfare of households, as well as, developing creative activities to generate employment.

2.3 Benefits of Renewable Energy Systems

There are many benefits associated with the installation and operation of renewable energy systems, which can be categorised into energy saving, generation of employments and decrease in environmental pollution. The energy saving advantage is derived from the decrease in consumption of electricity and diesel that are used conventionally to deliver energy. This benefit can be directly converted into monetary units, according to the equivalent reduction in fuel bills and company running costs. Another benefit is the ability of renewable energy technologies to generate employment as a means of economic development to a country. Introduction of a new technology will result in the establishment of new production activities, contributing to the production, market distribution and operation of the appropriate equipment. The global advantage of renewable energy systems is the reduction of environmental pollution. This is realized by decrease of the CO_2 emissions due to the replacement of fossil fuels with renewable energies (Kalogirou, 2004; Okuo *et al.*, 2016).

2.4 Types of Renewable Energy

2.4.1 Solar energy

In many parts of the world there is a growing awareness that renewable energy has an important role to play in the provision of social amenities, such as potable water and electricity, and in extending technology to farmers in developing countries to increase their productivity. Among the various types of renewable energy, special attention has been given to solar energy because it is freely available. Solar energy is the driving force behind several renewable forms of energy. Solar thermal technology is a technology that is rapidly gaining acceptance as an energy saving measure in all aspect of energy applications. It is fast becoming an alternative source of energy because of the high rate of depletion of the conventional energy sources. It is preferred to other alternative sources of energy such as wind and shale, because it is abundant, inexhaustible, and non-polluting (Adegoke and Bolaji, 2000; Bolaji, 2008a).

The earth and its atmosphere receive continuously 1.7 x 10^{17} W solar radiation per year. A world population with a total power need of 10 kW per person would require about 10^{11} kW of energy per year. It is thus apparent that if irradiance on only 1.0 % of the earth's surface could be converted into useful energy, then 10.0 % efficiency of the solar energy could provide all the energy needs of the people on earth. This figure is often quoted by solar energy enthusiasts, but unfortunately the nature of this energy source has technical problems, and economical limitations that are not apparent from this microscopic view of the energy budget. In spite of these limitations, solar energy is essentially inexhaustible and potentially capable of meeting a significant portion of the nation's future energy needs with minimum of adverse environmental consequence (Bolaji and Adu, 2007).

Solar energy potential in Nigeria

Nigeria like most tropical countries is blessed with large amounts of sunshine all year round. For instance, Nigeria receives about 490 W/m^2 of sunshine per day (Bamiro and Ideria, 1982). From the research carried out by Fagbenle (1991), in the month of August a very high insolation as much as 37639 kJ/m^2 was attained in Makurdi, Nigeria. Therefore, positive results are expected from solar energy utilization in Nigeria.

2.4.2 Ocean energy

Ocean covers more than 70% of the earth surface. As the world's largest solar collectors, they generate thermal energy from the sun. Ocean also produces mechanical energy from tides and wave. The wave energy devices are powered by the wind. Harnessing the power in ocean waves is one of the ways to extract energy from the sea. Wave power devices extract energy directly from surface waves or from pressure fluctuations below the surface (Sharma and Sharma, 2013). Renewable energy analysts believe there is enough energy in the ocean waves to provide up to 2 terawatts of electricity (a terawatt is equal to a trillion watts). Wave power cannot be harnessed everywhere. Areas rich in wave-power in the world include the western coasts of Scotland, Northern Canada, Southern Africa, Australia, and both the North-eastern and North-western coasts of the United States. In the Pacific Northwest alone, it is feasible that wave energy could produce 40 to 70 kW/m of western coastline (Poullikkas, 2014).

A process called Ocean Thermal Energy Conversion (OTEC) uses the heat energy stored in earth's oceans to generate electricity. OTEC works best when the temperature difference between the warmer (top layer of the ocean) and the colder (deep ocean water) region is about 20 ^oC. This condition exists in tropical coastal areas, roughly between the Tropic of Capricorn and the Tropic of Cancer (Myers *et al*., 1986).

2.4.3 Wind energy

For hundreds of years, people have used windmills to harness the wind's energy. Today's wind turbines, which operate differently from windmills, are much more efficient technologies. Wind turbine technology is simple, the wind spins the turbine blades around a central hub and the hub is connected to a shaft which powers a generator to produce electricity. However, turbines are highly sophisticated power systems that capture the wind's energy by means of new blade designs or *airfoils*. Wind turbines that provide electricity to the utility grid range in size from 50 kW to 2 MW. Large utility-scale projects can have hundreds of turbines spread over many acres of land. Small turbines, below 50 kW, are used to charge batteries, electrify homes, pump water for farms and ranches, and power the remote telecommunications equipment (Timmons *et al.*, 2014).

2.4.4 Geothermal energy

The world “geothermal” literally means “Earth” plus “heat”. The geothermal resource is the world’s largest energy resource and has been used by people for centuries. In addition, it is environmentally friendly. It is a renewable resource and can be used in ways that respect rather than upset our planet’s delicate environmental balance. The centre of the Earth is 4000 miles (6400 km) deep. This region is about 4000 ^oC or higher. Partially molten rock, at temperatures between 650 to 1200 ^oC, is believed to exist at depths of 80 to 100 km (Fridleifsson, 2001). Heat is constantly flowing from the Earth’s interior to the surface. Most types of geothermal resources result from concentration of Earth’s thermal energy within certain discrete regions of the subsurface.

2.4.5 Bio-energy

Bioenergy describes any energy source based on biological matter. Unlike oil, coal or gas, bioenergy counts as a renewable energy option, because plant and animal materials can be easily regenerated. It is often considered to be environmentally friendly because, in theory, the CO_2 released when plants and trees are burned is balanced out by the CO_2 absorbed by the new ones planted to replace those harvested. In its most narrow sense, bioenergy is a synonym to biofuel, which is fuel derived from biological sources, however, in its broader sense it includes biomass. Biofuels are non-fossil fuels. They are energy carriers that store the energy derived from organic materials (biomass), including plant materials and animal waste. They may be solid, such as fuel-wood, charcoal and wood pellets; liquid, such as ethanol, biodiesel and pyrolysed oils; or gaseous, such as biogas. They are produced through contemporary biological processes, such as agriculture and anaerobic digestion. Biofuels can be derived directly from plants, or indirectly from agricultural, commercial, domestic, and/or industrial wastes (Surakat *et al*., 2013; Waheed *et al*., 2014).

Biomass is organic matter derived from living or recently dead organisms and any by-products of those organisms, plant or animal. Biomass can be used as a source of energy and it most often refers to plants or plant-based materials that are not used for food or feed, and are specifically called lignocellulosic biomass. As an energy source, biomass refers to those crops, residues, and other biological materials that can be used as a substitute for fossil fuels in the production of energy (Oyelaran *et al*., 2015d). They can either be used directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel. Conversion of biomass to biofuel can be achieved by different methods which are broadly classified into: thermal, chemical, and biochemical methods

2.5 Applications of Solar Energy

Solar energy can be utilized in the following areas: solar electricity, drying, water heating, water pumping for drinking and irrigation.

2.5.1 Solar photovoltaic energy (solar electricity)

Photovoltaic energy is the conversion of sunlight into electricity through a photovoltaic cell, commonly called a solar cell (Adu and Bolaji, 2004). Sunlight is composed of photons or particles of solar energy. These photons contain various amounts of energy corresponding to the different wavelengths of the solar spectrum. When photons strike a photovoltaic cell, they may pass right through, be reflected, or be absorbed. Only the absorbed photons provide energy to generate electricity. When enough sunlight (energy) is absorbed by the material (a semiconductor), electrons are dislodged from the material’s atoms. Special treatment of the material surface during manufacturing makes the front surface of the cell more receptive to free electrons, so the electrons naturally migrate to the surface.

When the electron leaves their position, holes are formed. When many electrons, each carrying a negative charge, travel toward the front surface of the cell, the resulting imbalance of charge between the cell’s front and back surface creates a voltage potential like the negative and positive terminals of a battery. When the two surfaces are connected through an external load, electricity flows (Bolaji and Adu, 2007). Individual cells can vary in size from about 1 cm to about 10 cm across. However, one cell only produces 1 or 2 watts, which is not enough power for most applications. In order to increase power output, cells are electrically connected into a packaged weather-tight module. Modules can be further connected to form an array (Figure 4). The term array refers to the entire generating plant, whether it is made up of one or several thousand modules. As many modules as needed could be connected to form the array size.

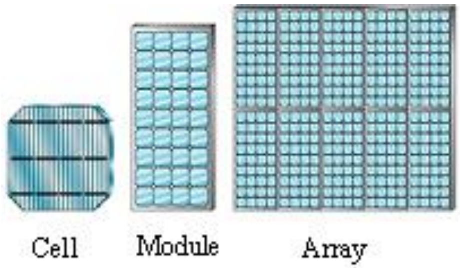
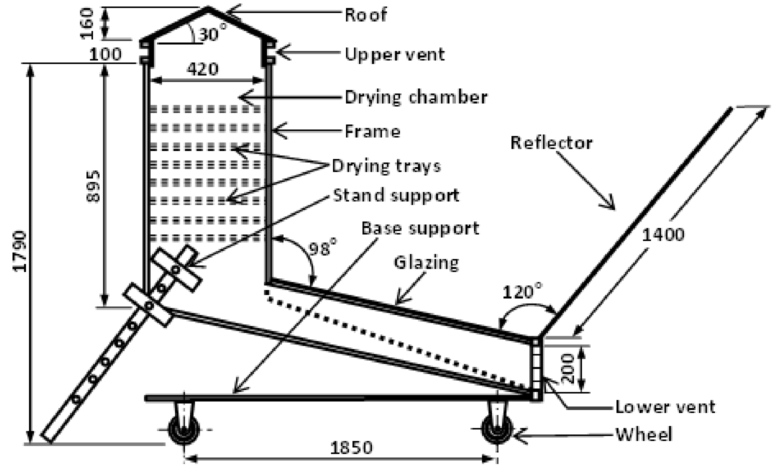


Figure 4: Different arrangement of solar cells
(Source: Oni and Bolaji, 2011)

2.5.2 Solar drying for food preservation

Food and energy are the essential factors for human survivals, so the efforts for greater food production and smaller energy dissipation can undoubtedly provide more peaceful and secured future for mankind. Losses of fruits and vegetables in developing countries are estimated to be 30 – 40% of production due to lack of good preservation methods and post-harvest handlings. One of the most important potential applications of solar energy is the solar drying of agricultural products. The postharvest losses of agricultural products especially in the rural areas of developing countries can be reduced drastically by using well-designed solar drying systems (Bolaji, 2005e; Akinola *et al*., 2006; Bolaji, 2008b). The air collector is the most important component of a solar food drying system. Schematic diagram of a mobile solar dryer is shown in Figure 5.



All dimensions in mm

Figure 5. A mobile solar dryer (Source: Olalusi et al., 2012)

2.5.3 Solar water heating system

Heating of water for domestic purposes is a simple and effective way of utilizing solar energy. A solar collector intercepts the incident solar radiation, converts it into heat, and finally transfers this heat to a working fluid for an end use system. The natural or free circulation solar water heating systems are most applicable in smaller installations (Figure 6).

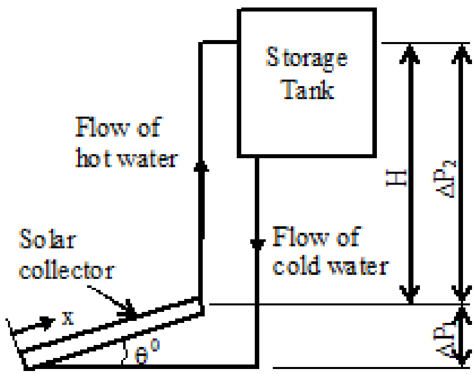


Figure 6: The schematic diagram of natural circulation solar water heater (Source: Bolaji, 2006b)

These are natural choice for domestic solar hot water systems (Bolaji, 2006b). The circulation of water between the solar collectors and the heat store is by gravity or thermosyphon action, whereas in the forced convection system, an electric pump is used for the water circulation which adds to the cost, energy consumption and complexity of the system (Bolaji, 2011a).

2.5.4 Solar photovoltaic pumping system

The use of solar photovoltaic as the power source for pumping water is considered as one of the most promising areas of PV application. Solar photovoltaic powered water pumping systems require only that there be adequate sunshine and a source of water. The use of photovoltaic power for water pumping is appropriate, as there is often a natural relationship between the availability of solar power and the water requirement. The water requirement increases during hot weather periods when the solar radiation intensity is high and the output of the solar array is at its maximum. On the other hand, the water requirement decreases when the weather is cool and the sunlight is less intense (Bolaji and Adu, 2007).

Solar photovoltaic water pumping systems are particularly suitable for water supply in remote areas where no electricity supply is available. Water can be pumped during the day and stored in tanks (Figure 7), thereby, making water available at night or when it is cloudy. The pumped water can be used in many applications such as domestic use, water for irrigation and village water supplies. The advantages of using water pumps powered by photovoltaic systems include low maintenance, ease of installation, reliability and the matching between the powers generated and the water usage needs. In addition, water tanks can be used instead of batteries in photovoltaic pumping systems.

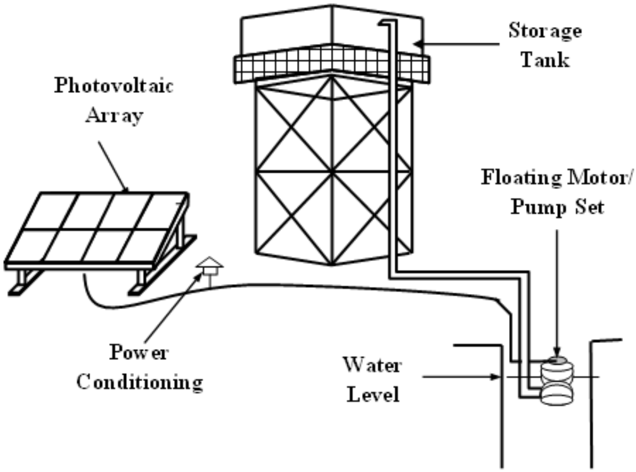


Figure 7: Solar photovoltaic pumping system (Bolaji and Adu, 2007)

2.5.5 Solar refrigeration

Most conventional refrigeration systems operate with electricity, however, there are regions where it is difficult or not cost efficient to provide electric service. Therefore, an alternative way of providing refrigeration to communities lacking conventional energy sources is through solar refrigeration.

The solar cooling technologies are mainly classified into two main groups depending on the energy supply: a thermal/work driven system and electricity (Photovoltaic) driven system.

Each group can be classified as the following:

(a) Thermal/work driven system
- Absorption refrigeration cycle
- Adsorption refrigeration cycle
- Chemical reaction refrigeration cycle
- Desiccant cooling cycle
- Ejector refrigeration cycle

(b) Electricity (Photovoltaic) driven system
- Vapour compression refrigeration cycle
- Thermo-electric refrigeration cycle
- Stirling refrigeration cycle

The solar-powered cooling system generally comprises of three main parts: the solar energy conversion equipment, the refrigeration system, and the cooled object (e.g. a cooling box). Solar photovoltaic (PV) power system applications are increasing due to both technical and economic factors. This type of solar refrigeration is very important for the storage of vaccines used in the extensive immunisation programmes, for the fight against the common communicable diseases throughout the developing world. During these programmes, all the vaccines have to be kept within a limited temperature range throughout transportation and storage. The type of refrigeration known as the Vaccine "Cold Chain", is a major logistic undertaken in areas where electricity supplies are non-existent or erratic (such as frequent blackouts) (Kartoglu and Milstien, 2014). Solar power is therefore of great importance to health care. Solar photovoltaic (PV) power for refrigerators has great potential for lower running costs, greater reliability and a longer working life than refrigerators powered by petrol or diesel generators, which have been generally used in remote areas.

3. REFRIGERANTS AND ENVIRONMENTAL ISSUES

Refrigerants play important roles in modern life. They are among the most essential components of refrigeration systems, which offer essential societal benefits. Refrigeration systems are not only providing comfortable and healthy living environments, they are also regarded as necessities for surviving severe weather. They enable: food storage, transportation, production and storage of both medical and pharmaceutical materials, and prevent spreading of diseases. Refrigeration also makes many important production processes possible, increases workers' productivity, and provides comfort. The problem is not with refrigerants inside the systems, but with their release (Bolaji, 2008c).

Ammonia, carbon dioxide, sulphur dioxide and methyl chloride were the most commonly used refrigerants when mechanical refrigeration was first developed. The oldest refrigerant (ammonia) has some advantages over other refrigerants. It has a lower molecular weight, wider range of working temperature because of its high critical point, higher latent heat at vaporisation and easier leak detection. It also shows a relatively high Coefficient of Performance (COP) compared to the other refrigerants. However, ammonia (R717) has some disadvantages, especially when human health, safety and material consideration are taken into account (Bolaji and Huan, 2013a).

A class of chemical compounds called chlorofluorocarbon (CFC) refrigerants has been in widespread use since the 1930s in such diverse applications as refrigerants for refrigerating and air-conditioning systems, blowing agents for plastic foams, solvents for microelectronic circuitry and dry cleaning sterilants for medical instruments. It also serves as aerosol propellants for personal hygiene products and pesticides, and freezants for food (Bolaji, 2011b). The CFC refrigerants were invented in 1928 by Thomas J. Midgley, Jr. and his associates, all employed in a small private research laboratory at Dayton, Ohio, supported by General Motors Corporation. They appreciate the swiftness with which their invention was made; men of science had been trying to invent the refrigerants, with the unique combination of the properties embodied in the chlorofluorocarbon compounds, for at least 100 years before Midgley and his associates invented them (Bhatti, 1999).

Chlorofluorocarbons (CFCs) have a long and successful association with the refrigeration industry. CFC-12 or R12 was the first Chlorofluorocarbon refrigerant introduced in 1931. It has about the same boiling point as ammonia but in contrast to earlier refrigerants, it is non-flammable, non-toxic and shows low corrosiveness as well as excellent chemical stability. CFCs were also easy and inexpensive to produce and within a short time they were widely adopted. They were the most commonly used refrigerants except in some large scale industrial refrigeration equipment where ammonia is still used. CFCs started to decline only after the environmental hazards associated with their release into the atmosphere were internationally recognized to be among the principal causes of ozone depletion and global warming (Bolaji, 2012b). The Montreal Protocol’s restriction on the production and use of these refrigerants, led to their ultimate phase out for most uses (UNEP, 2000).

Hence, there is need to search for alternative refrigerants, which will fit to the requirements of vapour compression refrigeration cycles.

The linkage of the CFC refrigerants to the destruction of the ozone layer, which has recently been established, is attributable to their exceptional stability enabling it to survive in the atmosphere for decades, ultimately diffusing to the rarefied heights where the stratospheric ozone layer resides. The inventors of these refrigerants could not have visualized the ravaging effects of the refrigerants on the ozone layer. They intentionally pursued refrigerants with the exceptional stability that was imposed as one of the necessary requirements of the ideal refrigerant they were called upon to invent (Bhatti, 1999).The primary requirements of the ideal refrigerant in 1978 were as follow:

(i) it should have normal boiling point in the range of - 40 to 0 ^{o}C;
(ii) it should be stable;
(iii) it should be nontoxic; and
(iv) it should be non-flammable.

Also considered are a qualitative assessment of transport and thermodynamic properties such as, the desirability of a low viscosity, high latent heat, and operation away from the critical point. None of the refrigerants available at that time, including sulphur dioxide, carbon dioxide, ammonia, methylchloride, ethylchloride, and isobutane; could fit the requirements (Bolaji, 2008c). Table 5 shows the characteristic of the common refrigerants known in 1928.

Table 5. Characteristic of the common refrigerants known in 1928.

Refrigerants	**Characteristic**	**Flammability**	**Toxicity**
Air	Does not liquefy readily	Non-flammable	Nontoxic
Water	High freezing point	Non-flammable	Nontoxic
Carbon dioxide	Low critical point	Non-flammable	Nontoxic but asphyxiant
Ammonia	Satisfactory	Very slightly flammable	Toxic but gives ample warning

Sulphur dioxide	Satisfactory	Non-flammable	Toxic but gives ample warning
Methyl chloride	Satisfactory	Slightly flammable	Toxic and gives no warning
Methyl bromide	High freezing point	Slightly flammable	Toxic and gives no warning
Butane	Satisfactory	Highly flammable	Nontoxic

(Source: Bolaji, 2008c).

The CFC refrigerants fulfilled all the primary requirements and heralded an unprecedented revolution in the refrigeration and air-conditioning industry. Today, the litany of the requirements imposed on an ideal refrigerant has increased. The additional primary requirements now include zero ozone depletion potential and very low global warming potential (Bolaji *et al*., 2011a). The environmental concerns relating to ozone depletion and global warming were not dreamt of when Midgley and associates invented the CFC refrigerants. Therefore, the engineers have to begin searches for the alternatives to CFC refrigerants, which will fulfil these new requirements in addition to the earlier primary requirements for the ideal refrigerants.

3.1 The Refrigerant Generations

The first century of refrigerant was dominated by innovative efforts with familiar fluids in almost prototypical machines. The aim then was to use "whatever worked" and the goals were to provide refrigeration and later, durability. Nearly all of the early refrigerants were flammable, toxic and some were highly reactive. The second generation was distinguished by a shift to fluorocarbon chemicals. It focused on safety and durability which included the introduction of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) as well as continued use of ammonia and lesser use of hydrocarbons, to enable broader use in domestic refrigerators (Bolaji, 2005f; Calm, 2008). Midgley Jr. and his associates, Henne and McNary, scoured property tables to find chemicals with the preferred boiling point. They limited the search to those known to be stable, but neither toxic nor flammable. Commercial production of CFC began with R12 in 1931 and followed by R11 in 1932, but ammonia continued and remains today as the most popular refrigerant in large scale industrial systems especially for food and beverage processing (Bolaji, 2011b).

The third generation of refrigerants emerged due to the linkage of released CFCs to depletion of protective ozone-layer with focus on stratospheric ozone protection. The Vienna Convention and resulting Montreal Protocol forced the abandonment of Ozone-Depleting Substances (ODSs). Fluorocarbon chemicals retained the primary focus, with emphasis on hydro-chlorofluorocarbons (HCFCs) for interim (transitional) use and hydro-fluorocarbons (HFCs) for the longer term (Bolaji *et al*., 2015). The shifts sparked renewed interest in ‘‘natural refrigerants’’ most especially ammonia, carbon dioxide and hydrocarbons.

As the industry moves away from ozone-depleting, new findings and political debate of global warming have become daily events, especially in recent years. The fourth generation refrigerants address the issues of both ozone depletion and climate change (global warming) in addition to safety, stability and also focus on the reduced emission of greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) showed that most of the observed increase in globally averaged temperatures by scientists since the mid-20th century, is due to the observed increase in anthropogenic greenhouse gas concentrations. The IPCC report also showed that noticeable human influences now extend to other aspects of climate, including ocean warming, continental average temperatures, temperature extremes and wind patterns (Calm, 2008). Therefore, the Kyoto Protocol, pursuant to the United Nations Framework Convention on Climate Change (UNFCCC), sets binding targets for greenhouse gas (GHG) emissions based on calculated equivalents of carbon dioxide, methane, nitrous oxide, HFCs, perfluorocarbons (PFCs), and sulphur hexafluoride. National laws and regulations to implement the Kyoto Protocol prohibit avoidable releases of HFC and PFC refrigerants (Bolaji and Huan, 2012a). These restrictions are forcing shifts to a fourth generation of refrigerants defined by focus on global warming. Candidates being considered for fourth generation refrigerants are those that have zero ODP with very low GWP such as blends of natural refrigerants, water and air, low GWP HFCs and unsaturated fluorocarbons that meet market demands as well as the regulatory requirements. The refrigerant generations are as summarized in Figure 8.

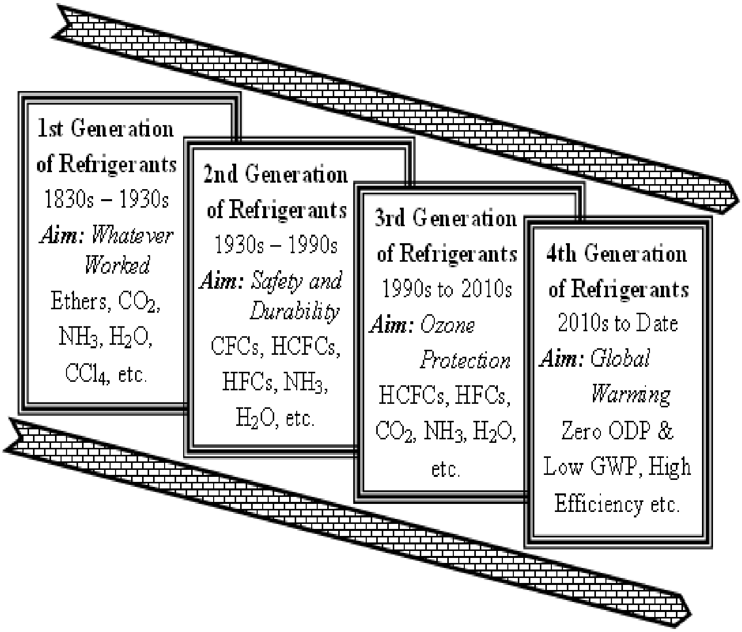


Figure 8. The refrigerant generations (Source: Bolaji, 2011b)

3.2 Environmental Issues

The depletion of the stratospheric ozone layer and global warming (climate change) are the two major environmental concerns with serious implications for the future development of the refrigeration-based industries. The effects on the industry of the actions to reduce ozone depletion and global warming are now apparent. These two global environmental issues have been in the focus of atmospheric research over the past four decades. They are two basically independent phenomena with respect to their anthropogenic causes (Bolaji, 2014a). However, given that ozone itself is a greenhouse gas, ozone depletion plays an important role in the global climate system. The human made chemicals with high ozone depleting potentials (CFCs and HCFCs) which are majorly responsible for the depletion of the ozone layer also have high global warming potentials (Bolaji *et al*., 2014a).

3.2.1 CFC refrigerants and stratospheric ozone depletion

The first major environmental concern to strike the refrigeration based industries was depletion of the stratospheric ozone layer as the result of the emission of anthropogenic (man-made) chemicals into the atmosphere (Bolaji *et al*., 2017a). Ozone layer surrounds the earth's stratosphere which is about 11 kilometres above the earth surface. Life on the earth has been safe-guarded for thousands of years because of this life-protecting layer. It acts as shield to protect the earth against the harmful ultraviolet radiation from the sun. The term "Ozone" comes from the Greek word meaning "smell" which is a reference to ozone's distinctively pungent odour. It is a poisonous gas and if inhaled can cause death (Kowalok, 1993). Ozone is a variant of oxygen; each molecule contains three oxygen atoms bonded together in the shape of a wide triangle. In the stratosphere, new ozone molecules are constantly created in chemical reaction fuelled by power from the sun. The process for making ozone starts off with oxygen molecules (O_2). When struck by the sun's rays, the molecules split apart into single oxygen atom (O) which is exceedingly reactive. Within a fraction of a second, the atoms bond with nearby oxygen molecules to form tri-atomic molecules of ozone, O_3 (Bolaji, 2005f).

The ozone depleting effect is caused by the migration of very stable refrigerants of the CFC to the upper atmosphere (stratosphere). It is generally accepted that in the stratosphere, the stable CFC refrigerants become involved in catalystic reactions which have the effect of breaking down ozone without first destroying the chlorine released from the CFCs. The most harmful CFCs have an active "ozone destroying life" in the stratosphere of over 100 years. Since ozone layer filters out harmful ultraviolent (UV) radiation which might otherwise reach the surface of the earth, its depletion could result in high concentration of UV radiation on the earth surface (Adegoke, 1994; Oyelami and Bolaji, 2015).

The importance of ozone layer

Ozone plays a critical role in screening harmful ultraviolet radiation. Because of the strong absorption of solar ultraviolet rays by Ozone in the stratosphere, it is virtually impossible for ultraviolet rays between 200 and 300 nm to penetrate to the earth's surface at 290 nm, the radiation is 350 million times weaker than at the top of the atmosphere. UV radiation is typically broken down into three parts (Figure 9). UVA (320 to 400 nm), UVB (280 to 320 nm), and UVC (200 to 280 nm). UVC is quickly absorbed by small amounts of ozone, so that none gets to the earth's surface. UVB is partially absorbed and about half of the UVA is absorbed by ozone or scattered (Newman, 1998).

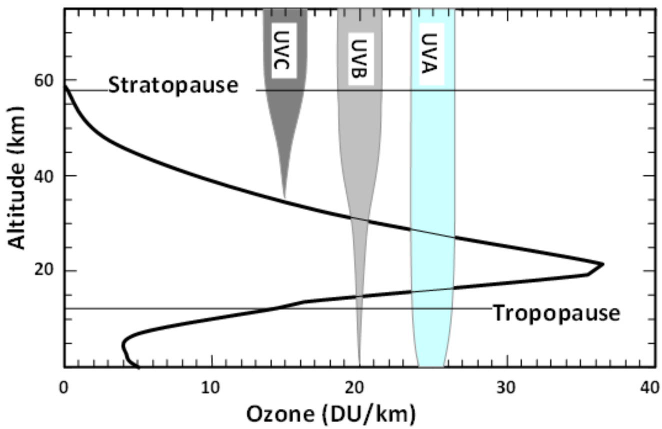


Figure 9. The Screening of UV by Ozone
(Sources: Newman, 1998; Bolaji, 2005f)

Effects of ozone depletion on human health

Laboratory and epidemiological studies demonstrate that UVB causes non melanoma skin cancer and plays a major role in malignant melanoma development. In addition, UVB has been linked to cataracts and immune system suppression. All sunlight contains some UVB, even with normal ozone levels. It is always important to limit exposure to the sun. However, ozone depletion will increase the amount of UVB and the risk of health effects (Bolaji, 2005f).

Effects of ozone depletion on plants

Physiological and developmental processes of plants are affected by UVB radiation, even at the amount of UVB in present-day sunlight. Despite mechanisms to reduce these effects and a limited ability to adapt to increase levels of UVB, plant growth can be directly affected by UVB radiation. Indirect changes caused by UVB (such as changes in plant form, how nutrients are distributed within the plant, timing of developmental phases and secondary metabolism) may be equally, or sometimes more important than damaging effects of UVB. These changes can have important implications for plant competitive balance, herbivores, plant diseases, and biogeochemical cycles (Newman, 1998).Other effects of ozone depletion are on marine ecosystems such as phytoplankton from the foundation of aquatic food webs and materials such as synthetic polymers, naturally occurring biopolymers, as well as some other materials of commercial interest are adversely affected by solar UV radiation (UNEP, 2000; Bolaji, 2005f). Therefore, any increase in solar UVB levels will therefore accelerate their breakdown, limiting the length of time for which they are useful outdoors.

Benefits of the CFC phase-out

The chlorofluorocarbon phase out is an important turning point in the recovery of the ozone layer and this will produce benefits for the environment, businesses, and individuals. The phase out of CFCs is expected to have direct health benefits, including reduced incidence of skin cancer and cataracts, decreased risks to human immune systems and increased protection of plant and animal life from excessive UV exposure. Also, CFC phase-out provided an impetus to develop and invest in a new generation of energy efficient refrigeration and air-conditioning equipment (Bolaji, 2005f).

3.2.2 Refrigerants and global warming

The second major environmental concern is climate change or global warming. This did not become a major area of attention until after the responses to ozone depletion had been initiated. Global warming arises because of the greenhouse effect. In a green house, glass allows sunlight in but prevents some infrared radiation from escaping (Bolaji, 2014b).

The gasses in the earth's atmosphere, which exert a similar effect, are called "greenhouse gasses". Some of these greenhouse gasses include CFCs, HCFCs, HFCs, CO_2, Methane (CH_4) and Nitrous Oxide (N_2O).

The frequency distribution of the radiation coming from the sun closely approximates the spectrum wavelengths range from less than 1 nm to hundreds of metres, and from a black body at a temperature of about 5800 K. The peak in the spectrum is in the visible region at about 500 nm. When solar radiation (1360 Wm^{-2}) arrives at the earth, about 30% is reflected back into space and most of the remainder passes through the atmosphere to the ground. This heats up the earth, which then behaves approximately as a black body, thereby radiating energy with a spectral peak in the infrared. This infrared radiation cannot pass through the atmosphere because of absorption by water vapour, and other infrared absorbers. As a consequence, heat energy is trapped and the temperature at the surface of the earth is higher than it would be without the insulating blanket of the atmosphere (Bolaji and Huan, 2013a).

Global warming is a good thing in itself and allows life to exist in all its variety. The scientific community as a whole has concluded that naturally occurring greenhouse gases have remained fairly constant over the past several hundred years. However, greenhouse gases directly and indirectly generated by mankind for the past 150 years have increased radically especially in the past 60 years (Calm, 2008). Ideal amounts of naturally occurring greenhouse gases, especially water vapour, are necessary to maintain the Earth's temperature at inhabitable levels. Without greenhouse gases, Earth's temperature would be too cold for human and most other life. The concern is that man's activities have increased the concentration of greenhouse gases in the atmosphere. The excessive upsurge in the greenhouse gases has increased the amount of the absorbed infrared radiation leading to increased atmospheric temperatures and consequent long-term climate changes (UNEP, 2000). This issue of global warming is very serious since it threatens the safety and lives of people. According to Bolaji *et al*. (2017b), the rise of the temperature may cause the polar glacier melt, to result in the elevation of the ocean level. This will destroy uncountable coastlines in the world and take away the bulk of the low sea-level islands. It may also turn many regions into deserts when the speed of the climate change is faster than that for migration of the vegetation zones.

Different gasses absorb and trap varying amounts of infrared. They also persist in the atmosphere for different time period and also influence atmospheric chemistry in different ways. The amount of radiant energy that the refrigerants absorb is measured by an index called global warming potential (GWP). GWP is the amount of infrared radiation that the gas can absorb relative to carbon dioxide (with an assigned GWP of 1) integrated over a period of 100 years. There are two types of global warming effects. The first is the direct global-warming effect that is due to the emission of refrigerants and other pollutants. The second type is an indirect global-warming effect, which results from the emission of carbon dioxide due to the consumption of energy obtained from the combustion of fossil fuels (Oil, natural gas, and coal). The combination of the two global-warming effects is known as the total equivalent warming impact (TEWI). Therefore, a more appropriate measure of a refrigerant contribution to global warming should be based on TEWI (Bolaji and Huan, 2013a).

3.2.3 Worldwide efforts to reduce the effects of ozone depletion and global warming

The discovery of the two major environmental problems, discussed above, has resulted in a series of international treaties demanding a gradual phase out of halogenated fluids. These began in 1985 with the Vienna Convention on the protection of the ozone layer and the Montreal Protocol on substances that deplete the ozone layer in 1987. Followed by London, Copenhagen, Vienna, Montreal and Beijing Amendments of 1990, 1992, 1995, 1997 and 1999 respectively (UNEP, 2000). The measures to phase out the production and use of materials with high ozone depletion potentials (ODPs) emanated from the Montreal Protocol and its amendments. They include chemicals containing chlorine and bromine used as refrigerants, solvents, foam blowing agents, aerosol propellants, fire suppressants, and for other purposes.

The CFC refrigerants have been phased out in developed countries since 1996, and 2010 in developing countries. Initial alternative to CFCs included some hydro-chlorofluorocarbons (HCFCs), but they will also be phased out in 2030 and 2040 in the industrialised and developing countries respectively. In Montreal, the EU pushed for an earlier HCFC phase out date 2015, but this was defeated following opposition by the United States, Canada, and some developing countries (UNEP, 2000; Bolaji and Huan, 2012b). The EU proposal was based on the increasing availability of non-depleting substitutes for HCFCs and on recent evidence that many HCFCs are acutely toxic following regular exposure. Meanwhile, different countries are adopting their own phase-out strategies. For example, Germany has banned the use of HCFC-22 (R22) in new plants after the year 2000 (McMullan, 2002). In agreement with the Montreal protocol, many refrigerants containing CFCs and HCFCs were increasingly replaced with hydro-fluorocarbons (HFCs) which have zero ozone depletion potential (ODP) but their global warming potential (GWP) is relatively high. The HFC refrigerants are considered as one of the six target greenhouse gases under Kyoto protocol. Kyoto protocol was approved by many nations, called for the reduction in emissions of greenhouse gases including HFC refrigerants. The presence of fluorine atoms in HFC refrigerants is responsible for the major environmental impact (Bolaji and Huan, 2013b; Bolaji and Huan, 2014b).

3.3 Natural Refrigerants

About 50 different substances have been more or less extensively used as working media over the 160 years of refrigeration history. Most of them have been discarded as unsuitable for various reasons, but a fair number of choice remains to adapt to varying conditions of application. Among them are a number of natural refrigerants such as water, ammonia, hydrocarbons and carbon dioxide. Natural refrigerants provide alternatives to a number of CFC, HCFC and HFC refrigerants. In addition to their zero ozone depletion potential and very low global warming potential (Table 6), they are compatible with common elastomer materials found in refrigerating systems and are soluble in conventional mineral oils (Bolaji and Huan, 2013a). Since natural refrigerants contain no chlorine or fluorine atoms, they cannot undergo reaction with water and hence, do not form the corresponding strong acids that can lead to premature system failure. The potentials of some of these refrigerants as viable alternatives to ozone depleting refrigerants and greenhouse gases are analysed below:

3.3.1 Ammonia refrigerant

Ammonia has been a well-known refrigerant in large scale industrial applications for more than 120 years. The know-how concerning the technology is widely dispersed in industrialised and developing countries. Ammonia has excellent thermodynamic and transport properties that are more superior to those of CFCs, HCFCs and HFCs. Ammonia plant always has considerably better energy efficiency in practice when compressor speed, piping dimensions and heat transfer equipment are decided on economic criteria. Other important advantages are tolerance to normal mineral oils, low sensitivity to small amounts of water in the system, simple leak detection, unlimited availability and low price (Bolaji and Huan, 2013a). All these factors contribute to its sustained popularity and wide application.

For large systems, the disadvantages of ammonia mainly concern safety; for small systems, there are presently additional cost disadvantages. The actual toxicity of ammonia is usually not a major concern; the smell is noticed by man at concentrations as small as 5 parts per million (ppm). At the same time, the threshold limit value, which should not be exceeded for everyday exposure, is 50 ppm. Ammonia is unbearable for man at 500 ppm, while its acute toxicity starts at 2500 ppm and the flammability at 15% volume. Obviously, any hazard announces itself in far advance, making ammonia actually a very safe refrigerant concerning direct hazards (Lorentzen, 1995; Bolaji, 2005f). However, there is an indirect hazard caused by use of ammonia in public areas: Heavy ammonia concentrations might cause (unnecessary) panic among those which are not familiar with the smell. The main focus of the safety measures is therefore to avoid a fast increase in ammonia concentration in public areas above the panic level. Hence, the safety rules for ammonia plants are very simple: No parts of a plant in direct contact with the public, and installation of systems to hold back significant ammonia amounts in case of a major rupture. While the former causes the need for indirect systems (which are always present in case of water chillers), the latter leads to housings around the systems, often combined with a water tank. The water in such a tank allows absorption of a significant amount of ammonia completely. About 50 litres of water can absorb 50 kg of ammonia. With such an amount, systems with up to 1.4 MW can be built (Lorentzen, 1995).

3.3.2 Hydrocarbon refrigerants

Hydrocarbons (HCs) are the class of naturally-occurring substances that include propane, pentane and butane. HCs are excellent refrigerants in many ways - energy efficiency, critical point, solubility, transport and heat transfer properties. They are environmentally sound alternative for CFCs, HCFCs and HFCs. Hydrocarbons and their mixtures have zero ozone depletion potential and very low global warming potential (Table 6), they have no significant refrigeration related problems. The most important concern regarding the adoption of hydrocarbons as a refrigerant is their flammability. It should be remembered that millions of tonnes of hydrocarbons are used safely every year throughout the world for cooking, heating, powering vehicles and as aerosol propellants. In these industries, procedures and standards have been developed and adopted to ensure the safe use of the product. It is essential that the same approach is followed by the refrigeration industry Bolaji, 2014c; Bolaji *et al*., 2014c).

Table 6: Environmental effects of some hydrocarbon refrigerants

Data	Refrigerants		
	Propane (R290)	n-butane (R600)	Iso-butane (R600a)
Natural	Yes	Yes	Yes
Ozone depleting potential (ODP)	0.0	0.0	0.0
Global warming potential (GWP)(100 years' horizon)	< 4.0	< 4.0	< 4.0
Density at 25°C (kg/m^3)	492.7	532.5	550.7
Flammability limits (% vol.)	2.1 – 11.4	1.7 – 10.3	1.9 – 10.0
Molecular mass (kg/kmol)	44.1	58.1	58.1

(Source: Bolaji and Huan, 2013a)

Hydrocarbons do not spontaneously combust on contact with air. Three elements need to coincide: (i) there must be a release of hydrocarbons; (ii) the hydrocarbon needs to mix with the correct proportion of air, the range of flammability being approximately between 1 and 10%. Outside these limits combustion cannot occur, and (iii) an ignition source with energy greater than 2.5 x 10^{-4} kJ or a surface with a temperature exceeding 440 °C must be present. Any of the following measures must be taken to prevent potential fire or explosion (Bolaji and Huan, 2012c):

(i) Contain the hydrocarbon either in a sealed system and/or reduce the number of connections.

(ii) Restrict the maximum charge of hydrocarbons.

(iii) Install ventilation such that the final concentration of hydrocarbons in air is below the lower flammability limit.

(iv) Eliminate the source of ignition associated with the system.

3.3.3 Water vapour refrigerant (R718)

Water has been looked at as refrigerant which is one of the ultimate natural refrigerants because of non-toxicity, non-flammability, zero-ODP, zero-GWP and very low cost. Water can be used as refrigerant in four ways: desiccant dehumidification/evaporative cooling, absorption chillers, adsorption chillers as well as compression chillers (Bolaji and Huan, 2013a). The thermo-physical properties of water are consistent with a vapour compression chillers system that has the potential to achieve a high COP. The open cycle water vapour systems are used occasionally for direct evaporation chilling in situations with low relative time of operation, when the high power consumption is of minor importance compared to investment and labour costs. The vapour volume to be compressed is enormous, in the same order of magnitude as for an open cold air cycle of similar capacity. Steam ejectors are normally applied (Lorentzen, 1995).

Water has also been proposed as a refrigerant in regular systems using turbo- or special rotary compressors. The physical dimensions of these machines become very large and price must be a problem. In the high temperature heat pump area on the other hand, water is an ideal working medium. It has been used extensively for many years in open systems for concentration of liquids by evaporation. Since the temperature lift is limited to what is required for heat transfer, the COP becomes very high, up to 20 or more in some cases. The low lift also permits the use of simple and relatively inexpensive single stage turbo compressors. For open or closed cycle heat pumps in a multitude of industrial applications, at the upward temperature range of 80 - 100 °C, water is the obvious choice.

3.3.4 Carbon dioxide refrigerant (R744)

Carbon dioxide (CO_2 or R744) is one of the few natural refrigerants, which is neither flammable nor toxic. It is inexpensive, widely available and does not affect the global environment as many other refrigerants. CO_2 has a GWP of 1, but the net global warming impact when used as a technical gas is zero, since the gas is a waste product from industrial production. CO_2 is an excellent alternative among the natural refrigerants, especially in applications where the toxicity and flammability of ammonia and hydrocarbons may be a problem. CO_2 has been regarded as favour across the broad spectrum of automotive, domestic and industrial refrigeration, and air conditioning systems (Bolaji, 2008c). The most important issues are to enhance the energy efficiency and reduce cost of the systems to an acceptable level.

R744 had been used as a refrigerant in the 1930s and 1940s in ships' refrigerator and other stationary systems. However, refrigerant capacity dropped rapidly when ships passed through tropical regions. R744 was abandon as a refrigerant because of lost capacity at higher ambient temperatures and the introduction of CFCs and HCFCs (Bolaji, 2008c). R744 has the most favourable environmental parameters among all alternatives. It is non-flammable and non-toxic, and has very low GWP. Also important, is the fact that it is not necessary to capture R744 refrigerant during the AC system refilling or reparation and at the end of life, which simplifies handling and introduces certain savings. Interest for using natural refrigerants especially R744 due to its favourable characteristics reappeared in late 1980s because of the increased awareness of environmental harmfulness of fluorocarbons.

The property that decisively defines behaviour of R744 in a refrigeration cycle is its low critical temperature (31.1^{o}C). Hence vapour compression cycle with R744 at ambient temperatures works usually partly above the critical point, and at much higher pressures than most halocarbon. Consequently, the process of heat rejection is not any more predominately condensation, but trans-critical vapour cooling with significant gaseous refrigerant temperature decrease inside gas cooler (heat exchanger).The refrigerant must be cooled in gas cooler in order to improve the overall cooling performance and the COP of the system, which will bring the exit temperature as close as possible to the ambient temperature. Also, multiport tube and fin technology is used to achieve highly efficient heat exchange in gas cooler (Bolaji, 2008c).

In general, R744 heat exchangers offer more capacity than any halocarbon refrigerant of the same components' size and possess capacity for further improvement in terms of enhancement of air side heat transfer. The system is becoming more package-friendly. However, it is a possible disadvantage that the operating pressure of the transcritical refrigeration system using R744 is too high. One way to overcome this high pressure disadvantage may be a choice of cascade refrigeration system, where carbon dioxide refrigeration system is pre-cooled by other refrigeration system.

4. MY RESEARCH CONTRIBUTIONS

4.1 Overview

My Vice-Chancellor Sir, Distinguished Scholars, Ladies and gentlemen, I have worked on the different areas of Thermo-fluid which is an aspect of Mechanical Engineering that involves the study of Energy Systems, Thermodynamics, Heat Transfer and Fluid Mechanics. Therefore, my major contributions are in the areas of renewable energy applications, refrigeration and air-conditioning systems, and the effects of conventional energy systems on the environment. Energy is a vital input for sustainable development and economic growth for any country, but it is widely accepted that the growth in conventional energy consumption that has been experienced for many years all over the world cannot continue indefinitely as there is a limit to our fossil fuel reserves. For this reason, some of my researches were centred on application of renewable energy systems. In my contributions, special attention has been given to solar energy because it is freely available, abundant, inexhaustible and non-polluting. Refrigeration and air-conditioning systems represent a key area of energy usage in both urban and rural households. Energy costs and environmental concerns have made energy optimisation a critical issue. Also, energy efficiency is a prime mover in reducing global warming emissions. Therefore, some of my researches focused on the environment-friendly refrigerants and energy efficient refrigeration systems.

4.2 Application of Solar Energy Systems

4.2.1 Solar water heating system

Heating of water for domestic purposes is a simple and effective way of utilizing solar energy. Solar water heating system is an alternative to the use of conventional energy for heating water. The system consists of two major components: a solar collector and hot water storage tank. A solar collector intercepts the incident solar radiation, converts it into heat, and finally transfers this heat to a working fluid for an end use system. Bolaji (1993) designed and constructed a flat-plate solar collector for heating water through energy from the sun. The system relied on the natural circulation of water between the solar collector and the hot water storage tank (Figure 10). The flat-plate solar collector consisted of a galvanised iron sheet blackened to enhance heat absorption and also corrugated in a special way to form tubular openings (grooves). Galvanised iron pipes were inserted into these grooves forming a continuous coil for the flow of water. The experimental results showed that the average hot water temperature was about 20 ^{o}C higher than the average ambient air temperature for the day time performance analysis. The analysis of overall daily results is shown in Table 7.

Figure 10. The experimental set-up of the solar water heating system (Source: Bolaji, 1993)

In order to improve the thermal efficiency of solar water heating system (Figure 11) and to correct some deficiencies noted in the system, some improvements and modifications were carried out on the system (Bolaji, 1997). The storage tank was properly insulated to reduce thermal losses and to increase hot water temperature (Figure 12). The water pipes were fully soldered to the heat absorber sheet to minimise the thermal contact resistance. The space between the water pipes was reduced from 83 to 53 mm in order to minimise the temperature difference between the tip of fin and the base. The heat transfer through the fin element of the collector absorber was taken into consideration in the design and appropriate fin efficiency factor was obtained. Also, the diameter of the collector water pipes was reduced from 20 mm to 17 mm and their number increased from 6 to 9 (Figure 13). These gave even spread of water along the absorber, thereby increasing the total heat gain.

Table 7: The analysis of overall daily results

Date	Ambient air (°C)	Solar radiation (W/m^2)	Hot water temperature (°C)	Average daily efficiency (%)
28/09/92	29.60	5353	50.00	34.0
29/09/92	29.30	5324	49.50	32.5
30/09/92	28.38	5625	50.50	34.2
05/10/92	28.93	5337	49.00	33.8
06/10/92	28.75	6155	52.00	36.1
07/10/92	29.40	5755	51.00	34.5
08/10/92	28.68	5875	51.00	35.9
09/10/92	29.93	6484	53.50	38.2
12/10/92	29.65	6194	53.00	37.3
13/10/92	29.45	6017	52.00	36.6

(Source: Bolaji, 1993)

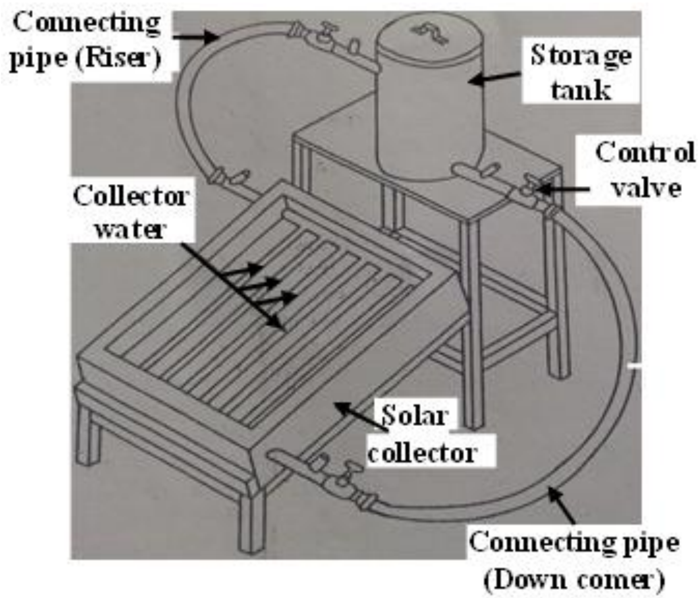
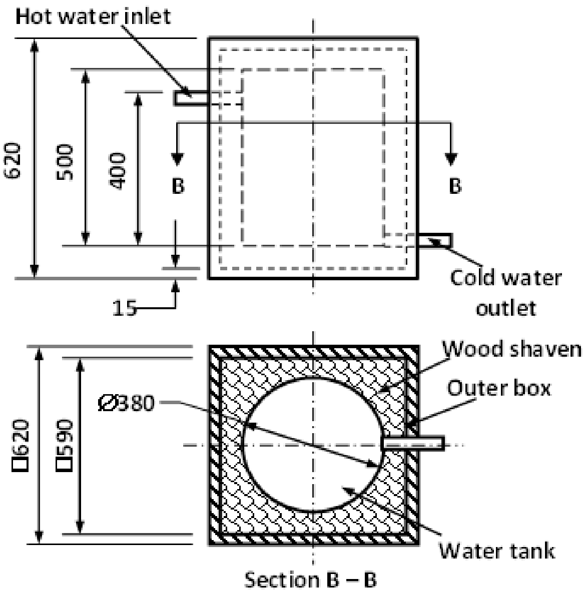
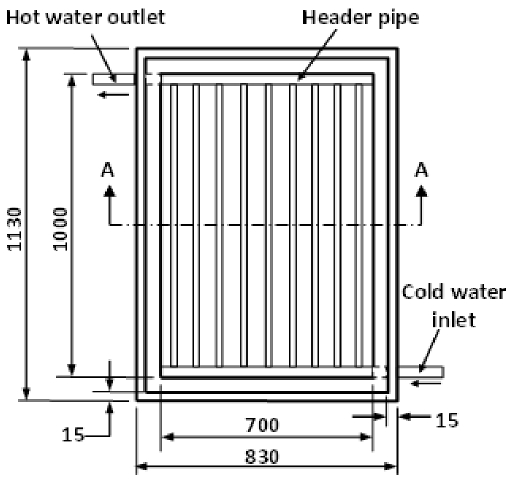


Figure 11. Schematic diagram of solar water heating system
(Source: Adegoke and Bolaji, 2000)



All dimensions in mm
Figure 12. Storage tank of the improved solar water heater
(Source: Bolaji, 2006b)



All dimensions in mm
Figure 13. Top view of the flat-plate solar collector
(Source: Bolaji, 2011a)

Adegoke and Bolaji (2000) conducted an experimental analysis on the two solar water heating systems (improved and the existing systems). The two systems were subjected to the same environmental and weather conditions and they were tested at Akure, Nigeria on Latitude 7.25^o N. The results showed that maximum temperatures of 53.5 and 76.5 ^{o}C (Figure 14) were obtained from the existing and the improved systems, respectively. Figure 15 shows the overall performance curves for both systems. The collector daily efficiency was found to increase with decreasing collector performance coefficient. The average daily efficiency of the improved system was 61 % while that of the existing system was 35 %.

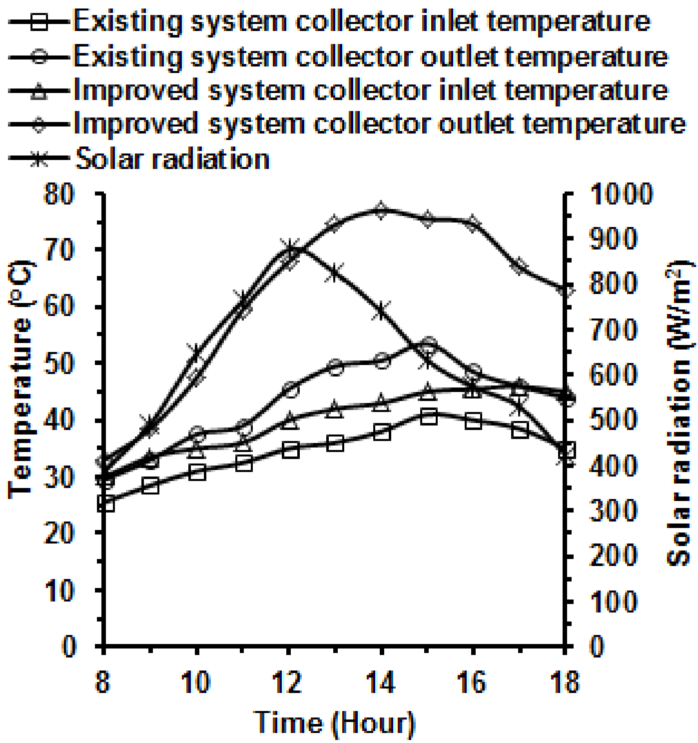


Figure 14. Typical daily temperature profile of the solar water heater (Source: Adegoke and Bolaji, 2000)

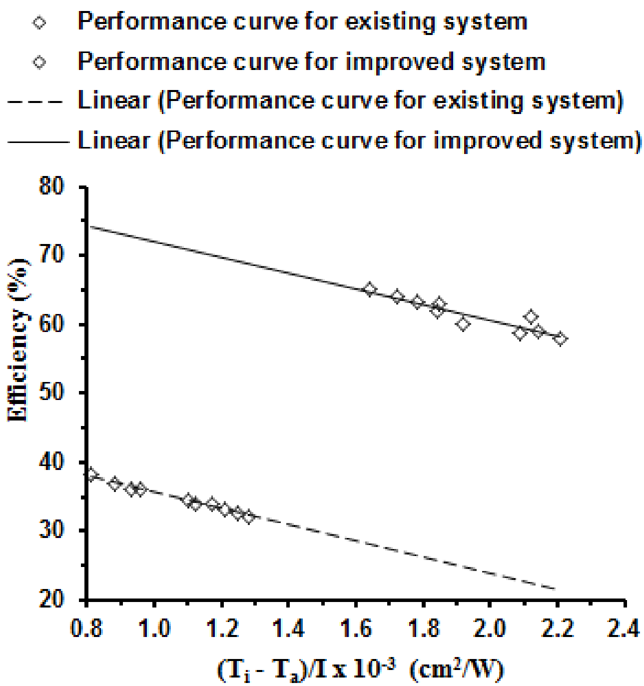


Figure 15. Performance curves for the solar water heaters
(Source: Adegoke and Bolaji, 2000)

Bolaji (2006b) developed a model for computing the relationship between the water flow rates of natural circulation of solar water heater and the collector performance. The fluid flow due to density gradient is usually termed the natural circulation or thermosiphonic flow. The magnitude of this flow was computed on the basis of simple physical principles. The schematic diagram of a natural circulation solar water heater is shown in Figure 6. It consists of a collector, a storage tank (installed above the collector) and the connecting tubes. The temperature difference causes a density variation which gives rise to buoyancy forces made up of two parts as follow:

$$\Delta P_t = \Delta P_1 + \Delta P_2 \quad (3)$$

where ΔP_1 = pressure difference due to the buoyancy force in the collector
ΔP_2 = Pressure difference due to the density variation in the connecting tubes.

The buoyancy pressure in the collector is calculated through integration over the length of the collector

$$\Delta P_1 = gSin\theta\int_0^L \left[\rho_{fi} - \rho_{(x)}\right]dx \qquad (4)$$

where $\rho_{(x)}$ = density of water at the location from the inlet of the collector

ρ_{fi} = density of water corresponding to temperature of water at the inlet of the collector.

Considering the density variation over the height H to be constant, the buoyancy force pressure ΔP_2 can be written as:

$$\Delta P_2 = \left(\rho_{fi} - \rho_{fo}\right)gH \qquad (5)$$

Substituting Eqs.. (4) and (5) in Eq. (3), we have

$$\Delta P_t = gSin\theta\int_0^L \left[\rho_{fi} - \rho_{(x)}\right]dx + \left(\rho_{fi} - \rho_{fo}\right)gH \qquad (6)$$

Over small temperature changes, the variations in density with temperature can be written as:

$$\rho_{(i)} = \rho_o\left(1 - \beta T_{(i)}\right) \qquad (7)$$

where β = coefficient of volume expansion of water

$\rho_{(i)}$ = density of water at temperature $T_{(i)}$

ρ_o = density of water at 0^oC.

Substitution of Eq. (7) in Eq. (6) yields

$$\Delta P_t = g\beta\rho_o\left[Sin\theta\int_0^L \left(T_{(x)} - T_{fi}\right)dx + H\left(T_{fo} - T_{fi}\right)\right] \qquad (8)$$

The total pressure losses ΔP_s in the system can be written as $\Delta P_s = \Delta P_c + \Delta P_z$

Where ΔP_c = Pressure losses in the collector

ΔP_z = pressure losses in the connecting tubes

Therefore, $$\Delta P_s = \Delta P_c\left[1 + \left(\frac{\Delta P_z}{\Delta P_c}\right)\right]$$

$$\Delta P_s = \Delta P_c\left(1 + r_p\right)$$

where $r_p = \frac{\Delta P_z}{\Delta P_c}$

In the stationary conditions of the flow, the total buoyancy pressure ΔP_t is equal to the total pressure losses ΔP_s, therefore,

$$\Delta P_t = \Delta P_c \left(1 + r_p\right) \quad (9)$$

Substitution of Eq. (9) in Eq. (8) yields

$$g\beta\rho_o\left[Sin\theta\int_0^L\left(T_{(x)} - T_{fi}\right)dx + H\left(T_{fo} - T_{fi}\right)\right] = \Delta P_c\left(1 + r_p\right) \quad (10)$$

Considered temperature distribution in the collector to be linear, therefore,

$$T_{(x)} - T_{fi} = \left(T_{fo} - T_{fi}\right)\left(\frac{x}{L}\right) \quad (11)$$

Hence $\int_0^L\left(T_{(x)} - T_{fi}\right)dx = \left(T_{fo} - T_{fi}\right)\left(\frac{L}{2}\right)$ (12)

Substitution of Eq. (12) in Eq. (10) yields

$$g\beta\rho_o\left(T_{fo} - T_{fi}\right)\left(½LSin\theta + H\right) = \Delta P_c\left(1 + r_p\right) \quad (13)$$

To obtain the relationship between the temperature and the mass flow rate ($\hat{m}$), the equation for useful heat energy collected Q_u can be used (Bolaji, 1997).

$$Q_u = A_c F_R\left[I\alpha\tau - U_L\left(T_{fi} - T_a\right)\right] \quad (14)$$

Where, A_c = Collector area (m^2)
F_R = Useful heat energy collected (W)
U_L = overall loss coefficient of the collector ($Wm^{-2}K^{-1}$)

The energy collected is converted to the thermal energy of water in the pipes, thus

$$Q_u = \hat{m}C_p\left(T_{fo} - T_{fi}\right) \quad (15)$$

Then $\hat{m}C_p\left(T_{fo}-T_{fi}\right)=A_cF_R\left[I\alpha\tau-U_L\left(T_{fi}-T_a\right)\right]$

Therefore, $\left(T_{fo}-T_{fi}\right)=\dfrac{A_cF_R}{\hat{m}C_p}\left[I\alpha\tau-U_L\left(T_{fi}-T_a\right)\right]$ (16)

Elimination of ($T_{fo}-T_{fi}$) from Eqs (11) and (14) yields

$$\hat{m}=\frac{A_cF_R}{\Delta P_c}\left[\frac{g\beta\rho_o}{\left(1+r_p\right)C_p}\right]\left[I\alpha\tau-U_L\left(T_{fi}-T_a\right)\right]\left(½LSin\theta+H\right) \quad (17)$$

The mass flow rate of natural circulation was computed using Eq. (17).The collector efficiencies at various flow rates were obtained and the results obtained shown that the efficiency increases as the flow rate increases until it reaches its maximum value of 0.1 kg/s per m^2 of collector area after which any additional increase in the flow rate no longer affects the performance of the collector. The collector efficiency at the optimum flow rate was 68.5% (Figure 16).

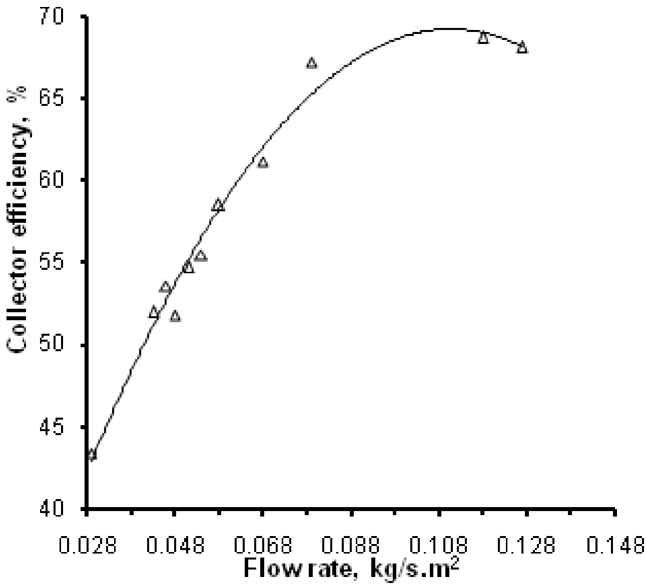


Figure 16. Efficiency as a function of water flow rate
(Source: Bolaji, 2006b)

The heat transfer in a flat-plate solar collector of a thermosiphonic solar water heating system was investigated theoretically and experimentally by Bolaji and Abiala (2012). The overall heat loss coefficient (conductance) was formulated using the energy balances on the collector absorber plate and detailed analysis of all heat losses through the flat-plate solar collector. At some typical location on the absorber plate where temperature is T_p (Figure 17), amount of solar energy absorbed per unit area by the plate is represented by "I".

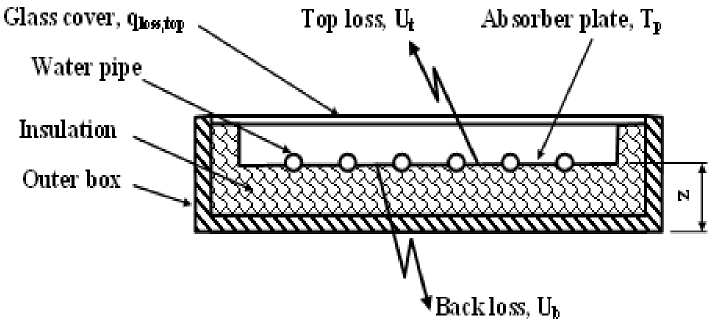


Figure 17. A schematic diagram of a flat-plate solar collector with water pipes (Source: Bolaji and Abiala, 2012)

This absorbed energy is distributed to losses through the top, back, edges and to useful energy gain. The energy loss through the back of the collector is due to the resistance to heat flow through the insulation, U_b, therefore,

$$U_b = \frac{k}{z} \tag{18}$$

where, k = insulation thermal conductivity (W/m.^{o}C); and z = insulation thickness (m).

The loss coefficient for the top surface is the results of convection and radiation between parallel plates. The heat transfer between the plate at temperature T_p, and the cover glass at temperature T_g, is equal to the heat lost to the surroundings from cover glass. The loss through the top per unit area ($q_{loss,top}$) is:

$$q_{loss,top} = h_{pg}\left(T_p - T_g\right) + \frac{\sigma\left(T_p^4 - T_g^4\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1} \quad (19)$$

where h_{pg} = heat transfer coefficient between plate and cover glass (W/m^2.^{o}C); T_p = temperature of the collector absorber plate (^{o}C); T_g = temperature of the collector cover glass (^{o}C); σ = Stefan Boltzman constant; ε_p = emittance of the absorber plate; ε_g = emittance of the cover glass.

If the radiation term is linearized, the radiation heat transfer coefficient can be used and the heat loss becomes:

$$q_{loss,top} = (h_{pg} + h_{R,pg})(T_p - T_g) \quad (20)$$

where, $h_{R,pg}$ = radiation heat transfer coefficient between cover glass and surrounding (W/m^2.^{o}C). Substitution of Eq. (20) in Eq. (19) yields:

$$h_{R,pg} = \frac{\sigma\left(T_p + T_g\right)\left(T_p^2 + T_g^2\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1} \quad (21)$$

The resistance to heat flow between plate and cover glass (R_{pg}, m^2.^{o}C/W) can be expressed as:

$$R_{pg} = \frac{1}{h_{pg} + h_{R,pg}} \quad (22)$$

The radiation resistance from the cover glass accounts for radiation exchange with the surrounding at T_s. Therefore, the radiation heat transfer coefficient between the cover glass and the surrounding ($h_{R,gs}$, W/m^2.^{o}C) can be written as:

$$h_{R,gs} = \frac{\varepsilon_g \sigma\left(T_g + T_s\right)\left(T_g^2 + T_s^2\right)\left(T_g - T_s\right)}{\left(T_g - T_a\right)} \quad (23)$$

The resistance to the surrounding (R_{gs}, m^2.^{o}C/W) can be expressed as:

$$R_{gs} = \frac{1}{h_w + h_{R,gs}} \quad (24)$$

For single glass cover system, the top loss coefficient from the collector plate to ambient (U_t, W/m^2.^{o}C) is:

$$U_t = \frac{1}{R_{pg} + R_{gs}} \tag{25}$$

Substitution of Eqs. (22) and (24) in Eq. (25) yields:

$$U_t = \left(\frac{1}{h_{pg} + h_{R,pg}} + \frac{1}{h_w + h_{R,gs}} \right)^{-1} \tag{26}$$

Therefore, the overall loss coefficient (U_L, W/m^2.^{o}C) is found by adding together the top and back loss coefficients, Eqs. (18) and (26):

$$U_L = U_t + U_b \tag{27}$$

Eq. (27) is used together with Eq. (14) to compute the heat gained by the collector (Q_c). The collector efficiency of solar heating systems (η_c) is the ratio of useful heat gain by the collector to solar radiation incident on the absorber of solar collector (Bolaji, 2011a), therefore,

$$\eta_c = \frac{Q_c}{A_c I} \tag{28}$$

Substitution of Eq. (14) in Eq. (28) yields:

$$\eta_c = F_R \left[\alpha\tau - U_L \frac{(T_{fi} - T_a)}{I} \right] \tag{29}$$

The theoretical and experimental results of variation of the collector efficiency with solar radiation are shown in Figure 18. The figure shows the dependence of the system performance on the solar radiation. The average collector efficiency of 65.4% obtained from theoretical analysis is slightly higher than that of experimental analysis (64.1 %).

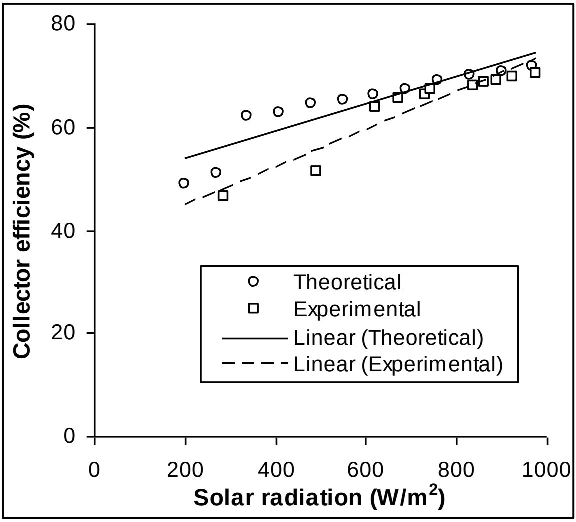


Figure 18. Variation of collector efficiency with incident solar radiation (Source: Bolaji and Abiala, 2012)

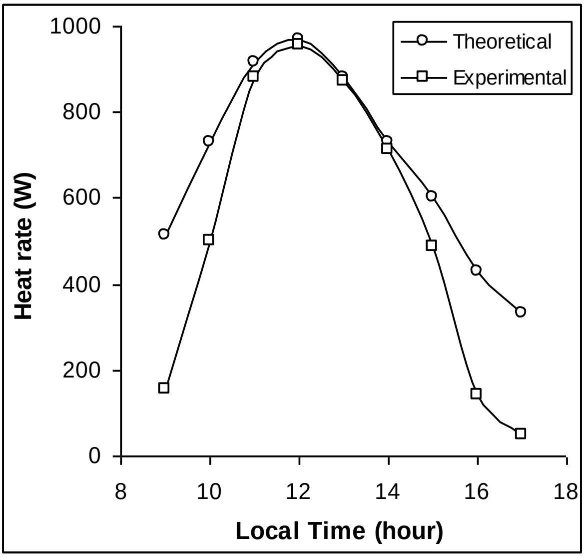


Figure 19. Variation of useful heat rate of the solar collector with time (Source: Bolaji and Abiala, 2012)

Figure 19 shows the variation of the useful heat rate of the solar collector with time. As shown in this figure, the useful heat rate is at its maximum around mid-day when the collector receives the highest energy, but it is low in the morning and late afternoon due to the low solar radiation during this period. Also, the difference observed between the theoretical and experimental results in the morning and late afternoon is due to the angle of incidence of the sun during these periods, which impairs the operation of the collector.

4.2.2 Solar photovoltaic (PV) systems

Bolaji and Adu (2007) developed a general method for designing simple photovoltaic pumping systems based on photovoltaic receiver driving electric pump. The information available from PV module and pump-motor manufacturers was used in the design analysis. In developing a mathematical solar cell model for photovoltaic pumping system, an equivalent circuit for a typical solar cell is considered as shown in Figure 20. Hence the relationship between current (I) and voltage (V) is obtained as:

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{A}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \qquad (30)$$

where: I_L = light current (A); I_o = dark current (A); I = operation current (A); V = operation voltage (V); R_s = series resistance (Ω); R_{sh} = shunt resistance (Ω) and A = thermal voltage (V).

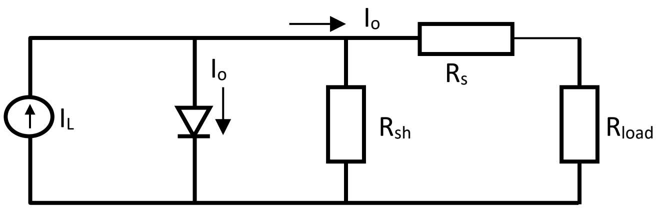


Figure 20. Equivalent circuit of a solar cell
(Source: Bolaji and Adu, 2007)

I_L, I_o, R_s, R_{sh}, and A are five parameters that depend on the incident solar radiation and the cell temperature. The shunt resistance R_{sh} is usually very large compared with the series resistance R_s, particularly for single crystalline silicon cells, therefore, the term $\frac{V + IR_s}{R_{sh}}$ in Eq. (30) is negligible, which reduced the parameters to four, and the equation can be rewritten as:

$$I = I_L - I_o\left[\exp\left(\frac{V + IR_s}{A}\right) - 1\right] \quad (31)$$

The results for the water flow rate and current as a function of voltage and water head for solar PV pumping system are shown in Figure 21.

Oni and Bolaji (2011) developed a universal d.c. power supply system in order to provide an uninterrupted power for d.c. appliances. The system employs simple Diode OR logic for the three power sources (mains from utility power supply, the solar photovoltaic and battery). Figure 22 shows a basic electric scheme of one PV cell. The current generator (I_c) provides a short-circuit current which is a function of the solar irradiation (G):

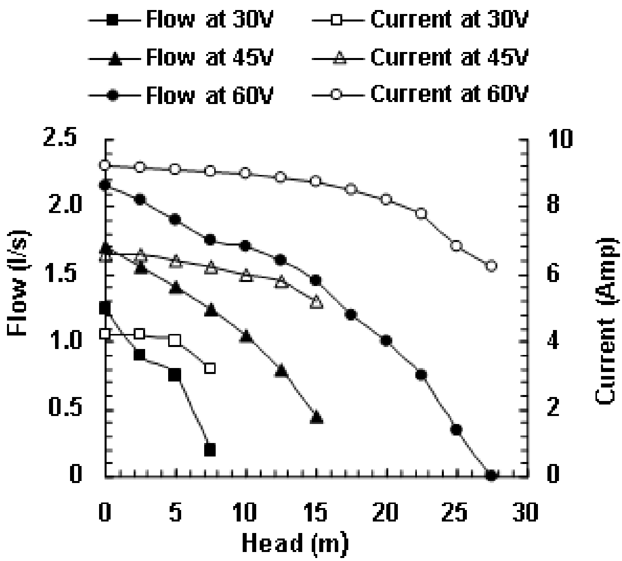


Figure 21. Flow and current as a function of head and voltage for solar PV pumping system (Source: Bolaji and Adu, 2007)

$I_c = a*G + b$ (32)

where, a and b are constants which depend on photovoltaic cells. 'D' is a diode whose parameters are given by simulations at the time of the modelling of PV generators. In this diode, the general equation of current (*I*) is given as:

$$I = I_s\left[\exp\left(\frac{q \cdot V}{\eta \cdot \sigma T}\right) - 1\right] \quad (33)$$

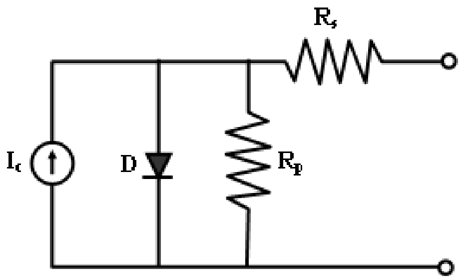


Figure 22. Electric scheme of one PV cell
(Source: Oni and Bolaji, 2011)

where, I_s = saturation current; η = idealist factor; V = voltage applied at the diode boundaries; q = electron charge; σ = Stefan Boltzmann constant; and T = temperature. Also, R_s and R_p in Figure 22 are resistances standing for the voltage drops per ohmic contact and leakage current. The complete circuit diagram for the universal power supply is shown in Figure 23. The basic operation of the circuit is centred on the characteristics of D_5-D_6, D_7 and D_8 network, which forms a 3-input Diode-OR logic gate. The parallel combination of these three diodes compares the output voltage of the three sources. In this arrangement, the highest voltage at a particular time feeds the d.c. output and supplies the charging current to the battery. The system outputs when all the three power sources were available, when solar and battery power were available (during utility power failure), and when only battery power was available, were 13.8, 13.1 and 12.2 V, respectively. The system can be used to power telecommunication equipment, audio-visual materials, computers, d.c. motor driven devices and other d.c. appliances.

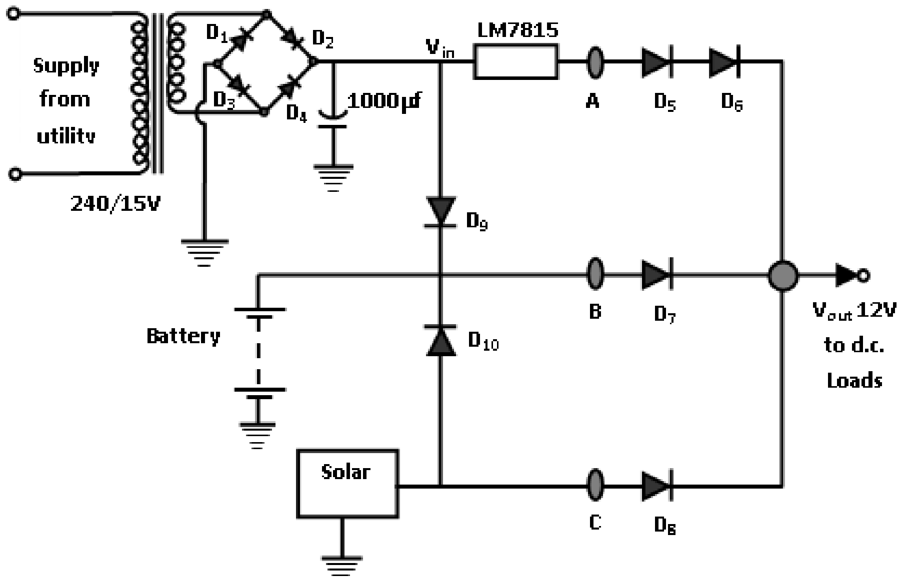


Figure 23. Universal power supply circuit
(Source: Oni and Bolaji, 2011)

4.2.3 Solar drying systems

Most agricultural products are produced during a relatively short growing season and the abundance is often highly perishable, harvested crops must therefore, be preserved for consumption until the next harvest season or for future use. Drying of agricultural products by the energy from the sun is one of the oldest agricultural techniques related to food preservation and the most widely practiced agricultural processing operation in the world. However, the old practice of simply spreading the items in the open had proved very unsatisfactory, hence, there is need for solar drying technology. Therefore, some of my researches focused on the design, construction and performance analysis of various solar drying systems. Bolaji (2005e) designed, constructed and tested a simple solar cabinet dryer for food preservation. Its construction was accomplished using mainly inexpensive locally available materials to make it relatively affordable to the average poor farmer (Figure 24). The dryer temperature was found to be above the ambient temperature by an average of 51 % throughout the day-light time.

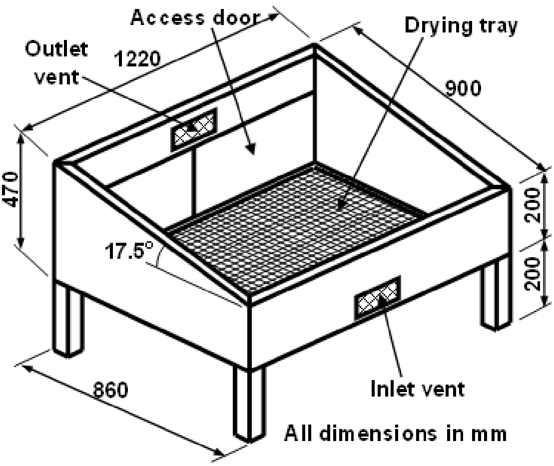


Figure 24: Solar cabinet dryer
(Source: Bolaji, 2005e)

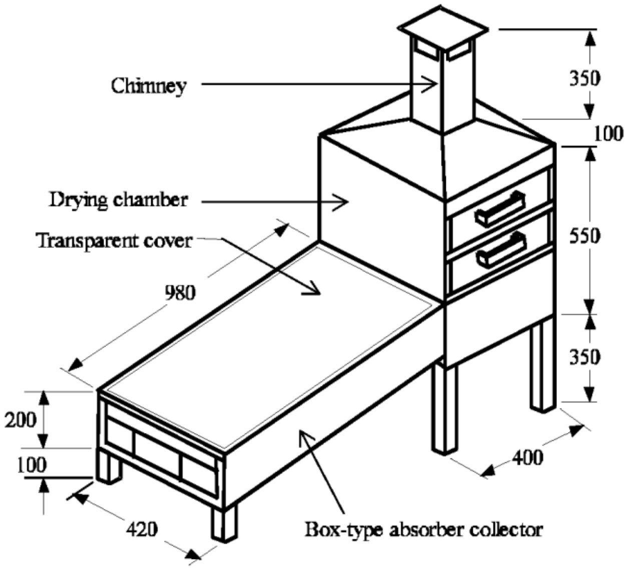


Figure 25. Solar crop dryer with box-type absorber air collector
(Source: Bolaji, 2005g)

Bolaji (2005g) developed box-type absorber solar air collector for crop drying (Figure 25). The box-type absorber is used with the aim of increasing the heat transfer area exposed to the flowing air through the collector in other to achieve high temperature and high efficiency with low friction losses in the system. The average temperatures obtained (during the day light) inside the collector and drying chamber were 64.0 ^{o}C and 57.0 ^{o}C respectively.

Bolaji and Olalusi (2008) develop a mixed-mode solar dryer in which the grains are dried simultaneously by both direct radiation through the transparent walls and roof of the cabinet and by the heated air from the solar collector (Figure 26). The results obtained during the test period revealed that the temperature inside the dryer was up to 74% for about three hours immediately after 12.00 (noon). Figure 27 shows the diurnal variation of the relative humidity of the ambient air and in the drying chamber. The drying processes were enhanced by the heated air at very low humidity as clearly shown in the figure.

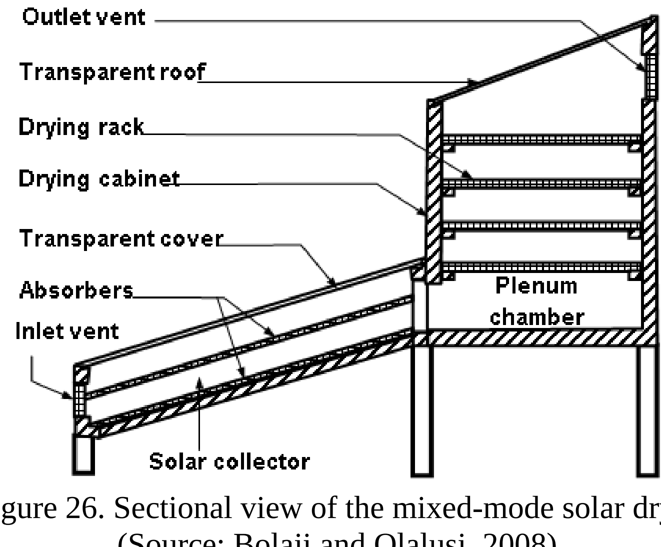


Figure 26. Sectional view of the mixed-mode solar dryer (Source: Bolaji and Olalusi, 2008)

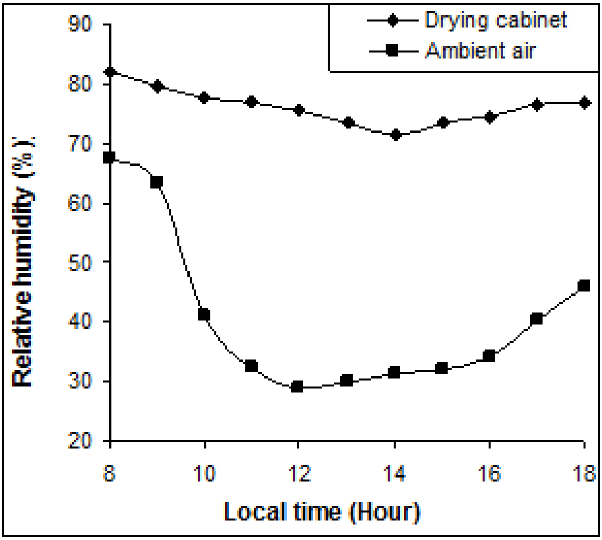


Figure 27. A typical day results of the diurnal variation of relative humidity in the mixed-mode solar dryer
(Source: Bolaji and Olalusi, 2008)

Moisture contributes greatly to the deterioration of agricultural products particularly in the tropics. Hence, it is necessary to consider moisture transport in drying of food items since the process involves the removal of moisture from the items to prevent the development of a favourable environment for the growth of moulds. Bolaji (2008b) analysed the mechanisms involved in the transport of moisture from food items during solar drying. Also a cabinet solar dryer for food preservation was designed, constructed, and the performance was evaluated using the concept of moisture transport in porous materials. Figure 28 shows the curves of moisture flux as a function of liquid concentration in the food items. It was observed that at lower liquid concentration, the moisture flux increases with increase in the liquid concentration, but the moisture flux was constant at liquid concentration above 70 kgm^{-3} for shelled corn and above 150 kgm^{-3} for yam chips which shows that yam chips are more hygroscopic than shelled corn.

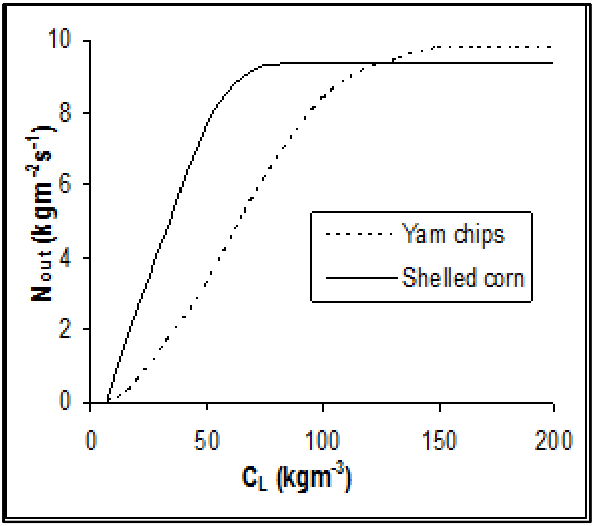


Figure 28. The moisture flux (N_{out}) as a function of liquid concentration (C_L) in solar drying of yam chips and shelled corn
(Source: Bolaji, 2008b)

Bolaji (2010a) developed a mathematical model for determining the dehydrative capacity of solar dryer. Figure 29 shows the representation of air evolution in a solar dryer on a psychrometric chart. The air at point 'a' enters the collector where it is heated at a constant pressure. Then, at point '1' it enters the drying enclosure, where it is isenthalpically humidified before leaving the dryer at point '2'. The water activity (a_w) is defined as the relative humidity of air in equilibrium with the material at the same temperature. If a_w is the water activity of food in the dryer, the maximum dehydrative rate of the product (D) in kg/s is:

$$D = \hat{m}_{da} (\omega_{2m} - \omega_a) \tag{34}$$

When air leaves the dryer in equilibrium with the product, $\omega_{2m} = \omega_2$, $\hat{m}_{da} = \hat{m}_{ha}$. Therefore, Eq. (34) becomes:

$$D = \hat{m}_{ha} (\omega_2 - \omega_a)$$

The partial vapour pressure in air (P_{va}) is calculated as:

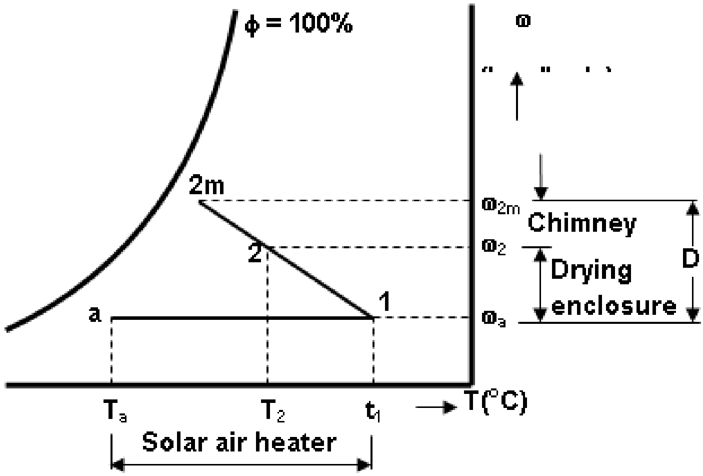


Figure 29. A psychrometric chart showing air evolution in a solar dryer (Source: Bolaji, 2010a)

$$P_{va} = \frac{\phi_a}{100} P_s(T_a) \tag{35}$$

With $$\log_{10}[P_s(T_a)] = 2708.2 - \frac{372544}{T_a} - 516.56 \log_{10}(T_a) \tag{36}$$

The thermal efficiency (η_c) of the solar collector is:

$$\eta_c = \frac{\hat{m}_{da} C_{pha}(T_1 - T_a)}{A_c I} \tag{37}$$

The corresponding wet bulb temperature (T_w) is determined by solving the following equation (Bolaji, 2010a):

$$P_{va} = P_s(T_{w1}) - \frac{C_{pha}(T_1 - T_{w1})[P_a - P_s(T_{w1})]}{0.622 L_v(T_{w2})} \tag{38}$$

with $L_v(T_{w1}) = (2.5018)10^6 - (2.378)10^3 T_{w1}$ (39)

Atmospheric air humidity ratio, ω_a is then determined from (Eastop and McConkey, 1996):

$$\omega_a = 0.622 \frac{P_{va}}{P_a - P_{va}} \tag{40}$$

and then the dryer outlet temperature T_2 is determined by solving the following equation:

$$a_w P_s(T_2) = P_s(T_{w2}) - \frac{C_{pha}(T_2 - T_{w2})[P_a - P_s(T_{w2})]}{0.622 L_v(T_{w2})} \quad (41)$$

In which it is assumed that $T_{w2} = T_{w1}$. The dryer outlet air humidity ratio is then obtained from:

$$\omega_2 = 0.622 \frac{P_{v2}}{P_a - P_{v2}} \quad (42)$$

with $P_{v2} = a_w P_s(T_2)$ (43)

Atmospheric air humidity ratio, ω_a is the ratio of mass of water vapour to the mass of dry air in a given volume of atmospheric air:

$$\omega_a = \frac{m_v}{m_{da}} \quad (44)$$

The concept of specific humidity is that if the mass of dry air (m_{da}) is 1 kg, then the mass of water vapour (m_v) associated with 1 kg of dry air will be ω_a kg (Eq. 44). Therefore, the total mass of air (m_a) is:

$$m_a = m_{da} + m_v$$

or $m_a = (1 + \omega_a)$ kg (45)

Finally, the sought dehydrative capacity (D_c) is dehydrating rate (Eq. 34) per unit mass of atmospheric air (Eq. 45) and is calculated from:

$$D_c = \frac{\hat{m}_{ha}}{1 + \omega_a}(\omega_2 - \omega_a) \quad (46)$$

The experiment conducted in the solar dryer using rough rice showed that the dryer has a dehydrative capacity of 0.5 kg/kg.h of atmospheric air at 52.2 % drying efficiency. Figure 30 shows the variation of dehydration rate of rough rice with time. As shown in the figure, dehydration is more effective between 11.00 and 15.00 hour.

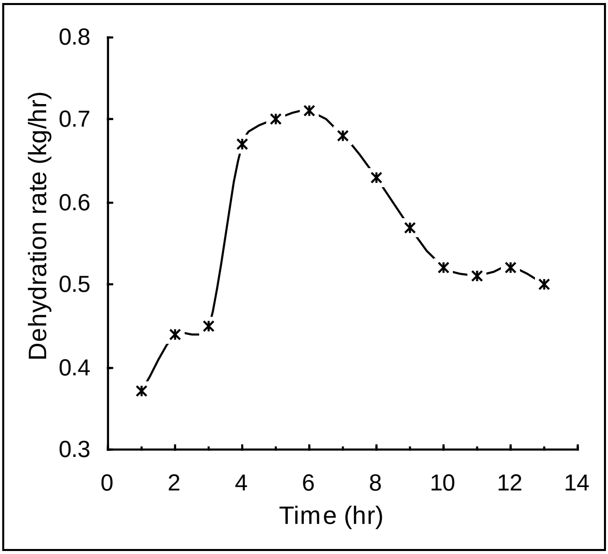


Figure 30. Dehydration rate for rough rice in the solar dryer (Bolaji, 2010a)

In order to achieve better drying rates, a proper circulation of heated air through the dryer is required. Meanwhile, electricity that will power the air circulation fan does not exist in most rural areas of developing countries, therefore Bolaji *et al*. (2011b) designed, constructed and tested a solar wind-ventilated cabinet dryer. A rotary wind ventilator was incorporated into the dryer, to increase the rate of air circulation through the dryer. Absorbed mesh screen was also added to the solar air heater to provide an additional heat transfer surface area (Figure 31).The drying of food items in the wind-ventilated cabinet dryer was compared with drying in a similar cabinet without wind ventilator and the former showed better results. The results also revealed that the system efficiency increased as the air velocity through the system increased.

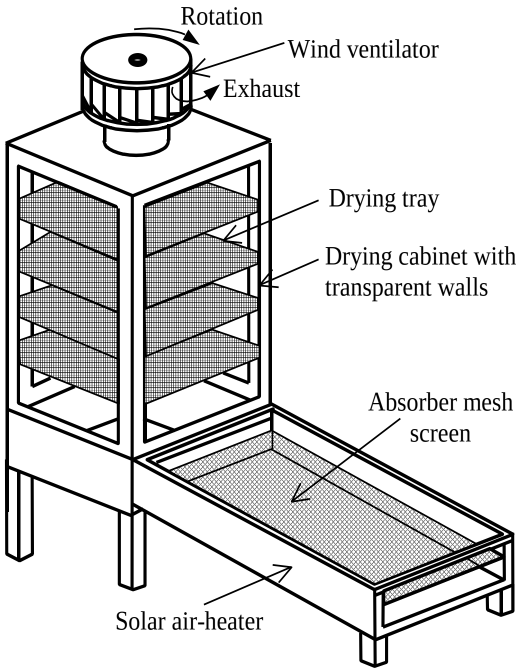


Figure 31. Solar wind-ventilated cabinet dryer (Bolaji et al., 2011b)

4.2.4 Exergetic Analysis of Solar Drying System

The ideal thermodynamic efficiency of a system is the ratio of useful work performed to the amount of energy supplied to the system. Since the solar collector absorbs energy at a higher temperature than the ambient, the energy will be partially converted to thermal energy in the system and partially lost to the environment. Therefore, for the evaluation of the thermal performance, such a system requires descriptive parameters to rate the availability of energy in the system. Most researchers in this area considered the pertinent performance indicator of solar system to be the collector's thermal efficiency, but Bolaji (2011c) employed a descriptive parameter (exergy) to analyse and rate the quantity and quality of energy absorbed by solar thermal systems.

In energy systems, not all the energy supplied is available to do work. The part of the supplied energy available to do the required work is

known as Heat Exergy, X, while the unavailable energy is known as Heat Anergy, Y (Adegoke and Bolaji, 1999).
Total energy, E = X + Y.

Heat exergy, $$X = \left(\frac{T_r - T_a}{T_r} \right) q \qquad (47)$$

where, q = rate of heat release (W); T_r = temperature at which heat is released (K) and T_a = ambient air temperature (K).

Heat anergy, $$Y = \left(\frac{T_a}{T_r} \right) q \qquad (48)$$

Eqs. (47) and (48) can be expressed as:

$$X = \gamma q \qquad (49)$$

$$Y = (1 - \gamma) q \qquad (50)$$

Where Exergetic potential, $$\gamma = \frac{T_r - T_a}{T_r} \qquad (51)$$

Eq. (49) can be written as

$$X_{in} = (\gamma_{in})(q_{in})$$

or $$X_{out} = (\gamma_{out})(q_{out})$$

Exergetic efficiency, η_x is defined as:

$$\eta_x = \frac{output\ exergy}{input\ exergy} = \frac{X_{out}}{X_{in}}$$

therefore, $$\eta_x = \left(\frac{\gamma_{out}}{\gamma_{in}} \right) \left(\frac{q_{out}}{q_{in}} \right) \qquad (52)$$

Thermal efficiency, η_{th} is:

$$\eta_{th} = \frac{useful\ output\ energy}{input\ energy} = \frac{q_{out}}{q_{in}} \qquad (53)$$

Therefore, Eq. (52) becomes

$$\eta_x = \left(\frac{\gamma_{out}}{\gamma_{in}} \right) \eta_{th} \qquad (54)$$

Exergetic analysis was carried out on three types of existing solar drying systems (direct, indirect, and mixed modes) to find the useful and the quality of energy that are obtainable from the systems. The results obtained show that mixed mode and indirect mode solar dryers are more effective in utilizing the captured energy than direct mode dryer. About 78.1% and 77% of the collected energy by mixed and indirect modes respectively is exergy or available energy (Figure 32), while 21.9% and 23% of the collected energy respectively is anergy or unavailable energy (Figure 33). But the direct mode system could only convert 49.3% of the collected energy to useful energy, while the rest 50.7% is wasted. Average exergetic efficiencies of 55.2%, 54.5% and 33.4% were obtained from mixed, indirect and direct systems respectively (Figure 34).

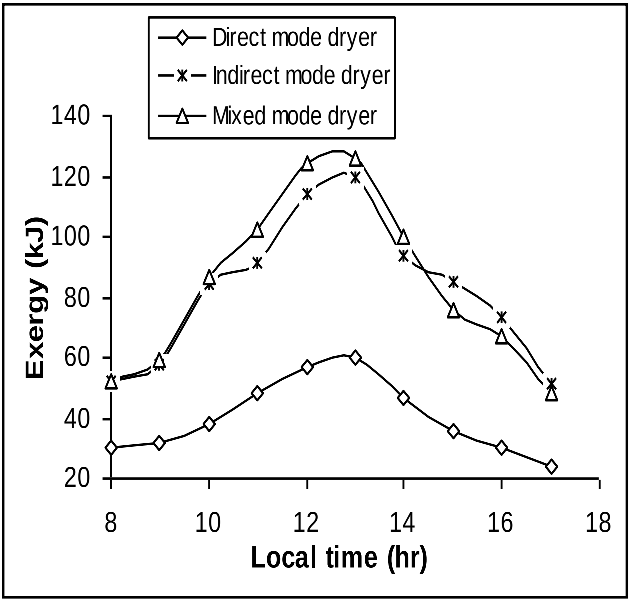


Figure 32. Variation of exergy with time in the solar dryers (Bolaji, 2011c)

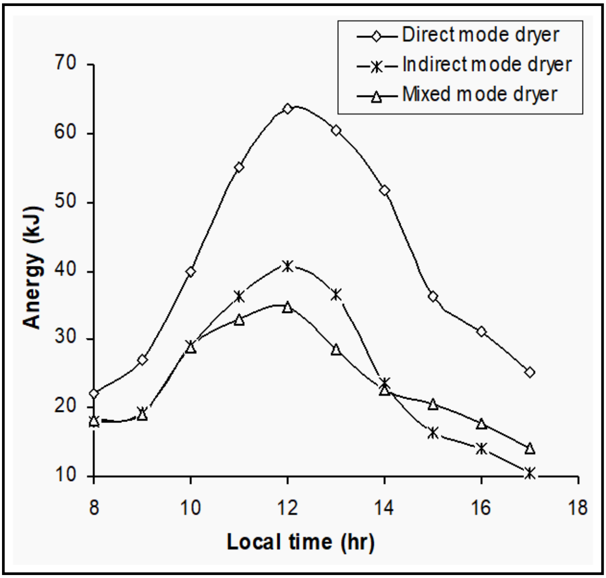


Figure 33. Variation of anergy with time in the solar dryers (Bolaji, 2011c)

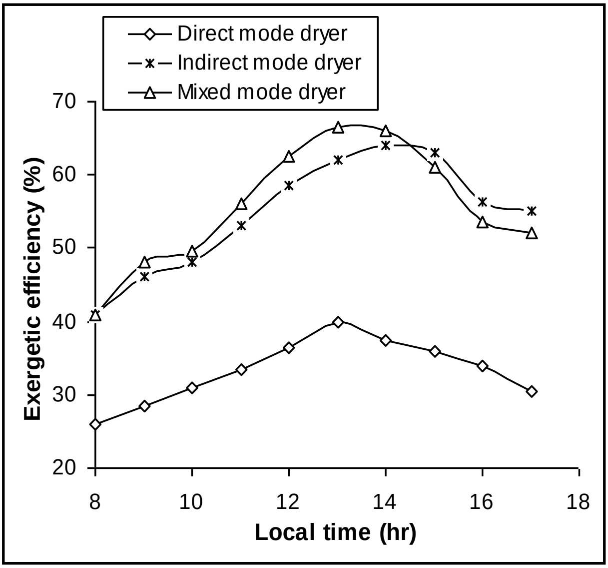


Figure 34. Variation of exergetic efficiency with time in the solar dryers (Bolaji, 2011c)

4.3 Combating the Negative Effects of Energy Systems on Environment

The demand for energy has increased due to industrial development and the improvement of living standards. This demand has so far been principally supplied by fossil fuels such as coal, gas and oil. However, the increase in energy consumption and the expansion of technology have been at the expense of other forms of life. Energy is directly implicated in the atmospheric pollution caused by the burning of fossil fuels for transportation, industry and domestic uses. Therefore, I also contributed in the area of combating the negative effects of conventional energy systems on environment.

Bolaji *et al*. (2018) investigated the major noise producing machines, the effects of the noise, and its control methods in the Nigerian manufacturing companies. Nine companies were chosen as models to represent the overall manufacturing sectors in Nigeria. The noise produced by the various machines and equipment used in the production processes in the companies was analysed. Results showed that electricity generating machines produced the highest overall percentage of noise (Figure 35). This is due to the continuous use of electricity generating sets as the prime power supply in all the nine studied companies. Electricity generating set supposed to be used intermittently as backup but the case here is different because the government own utility power supply is unreliable and erratic in nature (characterised by frequent blackouts). The effects of the noise will be severe in the industrial areas where many companies are sited together in the same area.

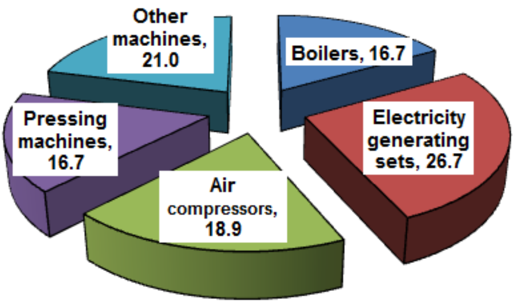


Figure 35. Overall percentages of noise produced by the machines in the studied companies (Bolaji et al., 2018)

Bolaji and Onipede (2005a) developed a pilot plant (Figure 36) for the recycling of used lubricating oil which was tested to evaluate the quality of the recovered oil. The results obtained showed that the viscosity and the flash point of the recovered oil are higher than that of the used oil but slightly lower than the virgin oil (Table 8).

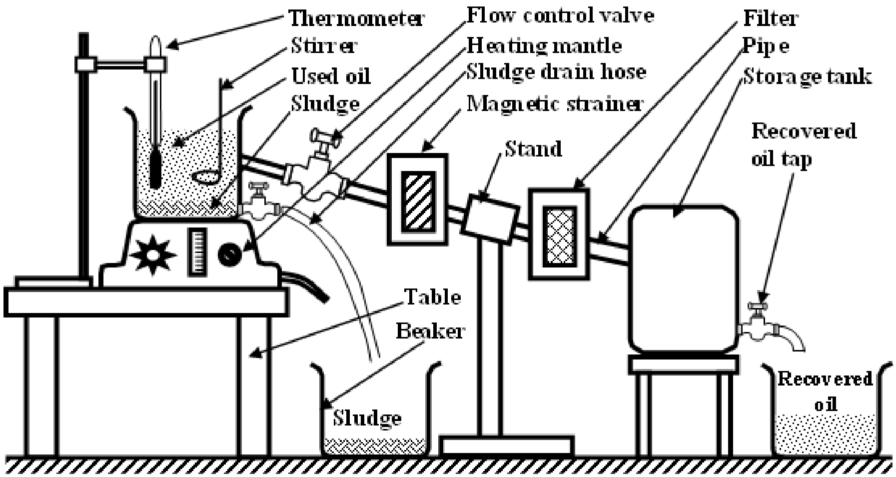


Figure 36. Pilot plant for used lubricating oil recycling
(Bolaji and Onipede, 2005a)

Table 8: Viscosity and flash point of virgin, used and recovered oils

Oil sample	Viscosity at Room Temp (cst)	Flash Point (°C)
Virgin oil	170.22	241.5
Used oil	121.12	152.5
Recovered oil	158.68	214.0

(Source: Bolaji and Onipede, 2005a)

Also, Bolaji and Onipede (2005b) conducted an optimization of vehicle silencer in order to minimise the noise level of the exhaust gases. Linear programming technique was employed to determine the best performance parameters that will give optimum efficiency with reduction in noise level. The results obtained from the optimization process formed the parameters used for the construction of the new (optimized) silencer (Figure 37). The optimised silencer was tested on selected motor cars and the experimental results showed its effectiveness in minimising the car exhaust noise level (Table 9).

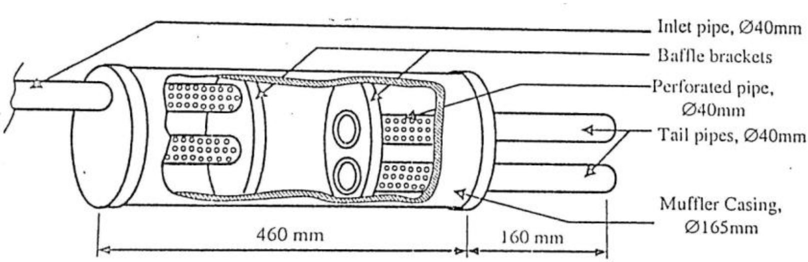


Figure 37. Optimized silencer (Bolaji and Onipede, 2005b)

Table 9: Noise level of the optimized silencer and the initial car silencer under idle speed

Car	Noise level (dB)		Reduction in noise level (%)
	Initial car silencer	Optimized silencer	
A	40.62	23.38	42.4
B	41.34	23.50	43.2
C	40.08	23.11	42.3
D	39.59	23.19	41.3
Average	40.39	23.30	42.3

(Source: Bolaji and Onipede, 2005b)

4.4 Environment-Friendly Refrigeration Systems

Chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) have been the traditional refrigerants used in refrigeration and air-conditioning systems, but due to the environmental concerns about their depletion of the earth's protective ozone layer and their global warming potential, their production and use have been prohibited completely all over the world. As a result, it became a very urgent issue to search for environmentally friendly refrigerants that will serve as CFCs and HCFCs substitutes.

4.4.1 Search for the environment-friendly refrigerants

In the search for the environment-friendly refrigerants, Bolaji (2008c) conducted a detailed analysis of various compositional groups of halocarbon refrigerants and their environmental problems. The research focused on the refrigerants found on the matrix triangles of methane and ethane derivatives for the selection of appropriate environment-friendly refrigerants (Figures 38 and 39). Trade-offs in flammability, toxicity, chemical stability and atmospheric lifetime scaled down the refrigerants to compounds occupying the remaining unshaded portion in Figure 40. Comparing Figures 38 and 39 with Figure 40, to select compounds without chlorine content, reduces the unshaded portion to the bottom row where we have R23 and R32 refrigerants in Figure 38, and R152a, R143a, R134a and R125 refrigerants in Figure 39. These refrigerants were further investigated to ascertain their suitability in vapour compression refrigeration systems.

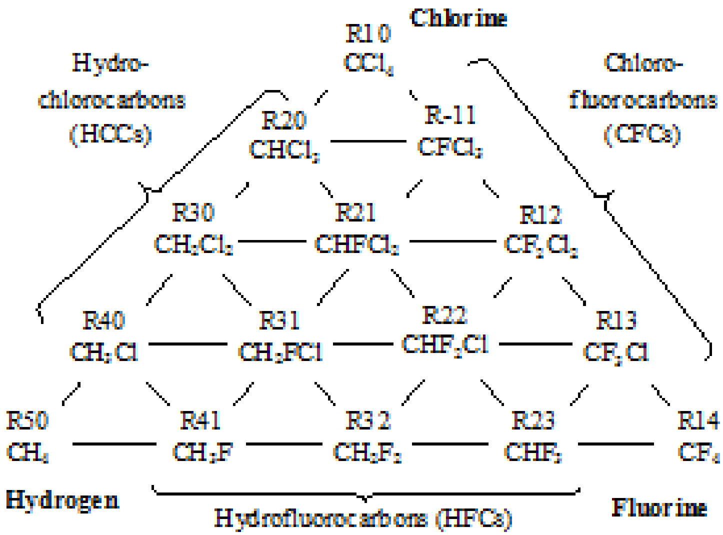


Figure 38. Derivatives of Methane (CH_4) (Bolaji, 2011b)

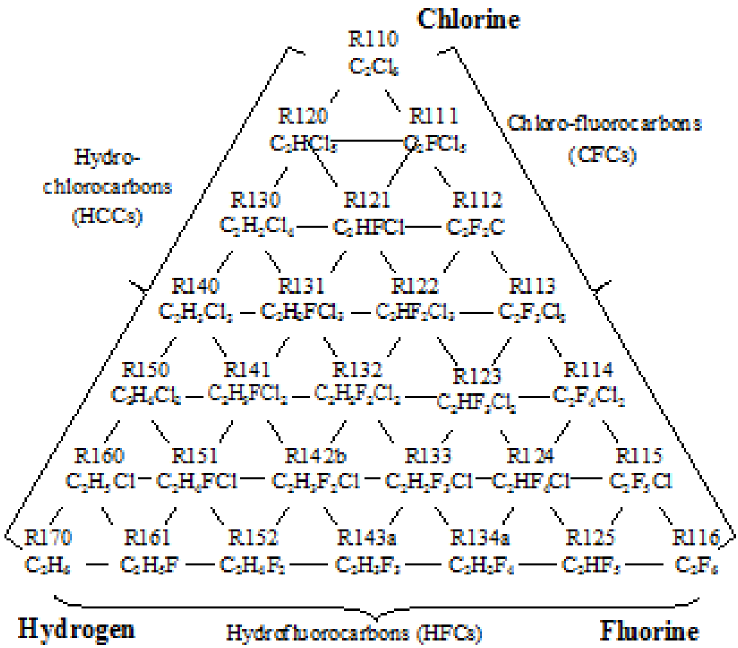


Figure 39. Derivative of Ethane (C_2H_6) (Bolaji, 2011b)

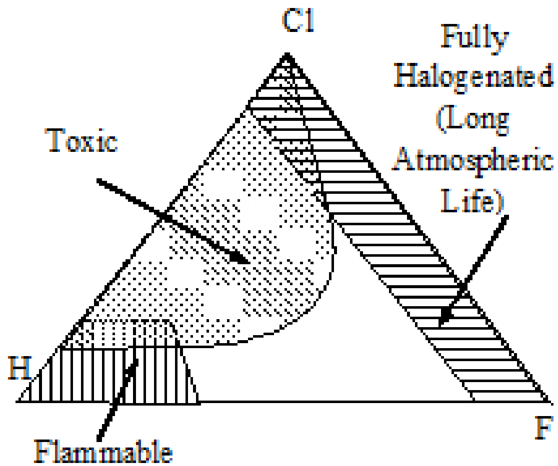


Figure 40. Trade-off in flammability, toxicity, and atmospheric lifetime with changes in molecular chlorine, fluorine and hydrogen contents (Bolaji, 2011b).

Bolaji *et al*. (2011a) experimentally investigated the performances of three ozone-friendly Hydrofluorocarbon (HFC) refrigerants (R32, R134a and R152a) in a vapour compression refrigeration system. The results obtained showed that R32 yielded undesirable characteristics, such as high pressure and low Coefficient of Performance (COP). Comparison among the investigated refrigerants confirmed that R152a and R134a exhibited very close performance. However, R152a has the highest COP, volumetric cooling capacity (VCC) and it also has the lowest GWP (Figure 41).

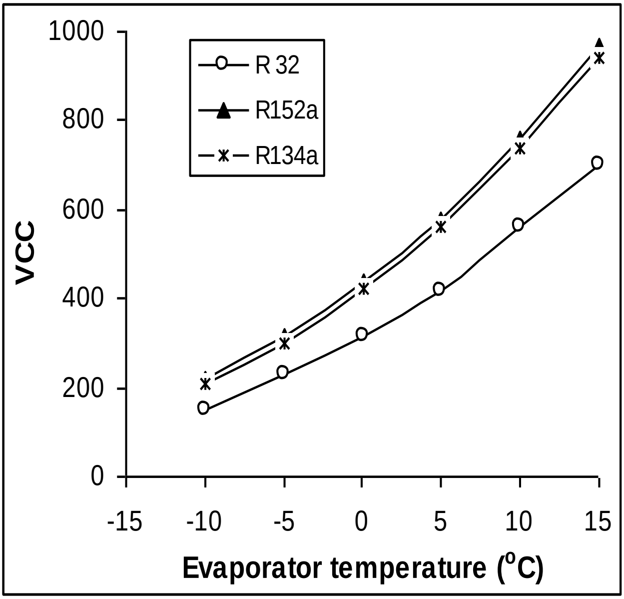


Figure 41. Variation of volumetric cooling capacity (VCC) with varying evaporator temperature for R32, R152a and R134a.

4.4.2 Development of test rigs for eco-friendly alternative refrigerants

My Vice-Chancellor Sir, Distinguished Scholars, Ladies and gentlemen, in my research work, I developed experimental test rig of a complete vapour compression refrigeration system with reciprocating compressor and with visual observation of all-important processes (Figure 42). The experimental results revealed a new discovery about R152a (Bolaji, 2010b) which was published by the Institution of Mechanical Engineers, UK.

The test rig was used to study five ozone-friendly alternative refrigerants (R23, R32, R143a, R134a and R152a) to determine their suitability in the conventional refrigerator. The temperature and pressure measurements were made at the four different points indicated in Figure 42. Temperatures were measured with copper-constantan thermocouple with accuracy of ±1°C. Pressures were measured with 24 V DC pressure transducers with accuracy of ±0.5 kPa. The energy consumption was measured with watt-hour meter with accuracy of ± 0.2 kWh. The results obtained as shown in Figure 43 revealed that the refrigeration capacities of R152a and R134a are similar to that of R12, while the refrigeration capacities of R143a, R32 and R23 are lower than that of R12. Also, the results coefficient of performance of refrigeration (COP) of the investigated refrigerants (Figure 44) showed that the COPs of R152a and R134a are similar to that of R12.

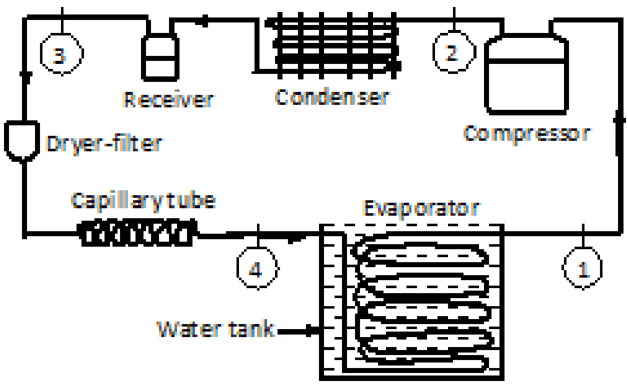


Figure 42. Experimental apparatus of vapour compression refrigeration system (Bolaji, 2010b)

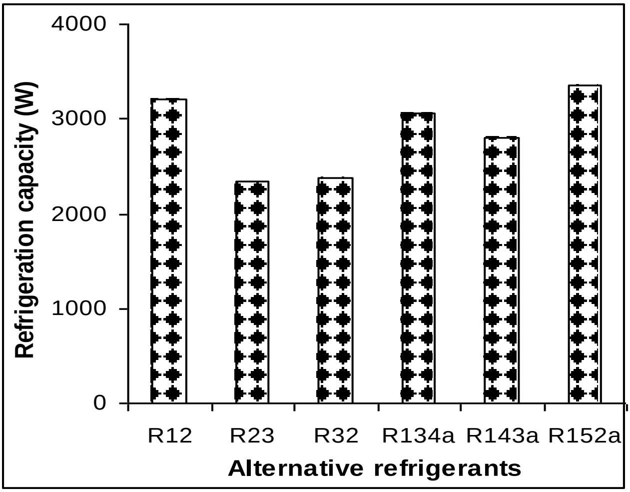


Figure 43. Refrigeration capacity of alternative refrigerants compared with R12 (Bolaji, 2010b)

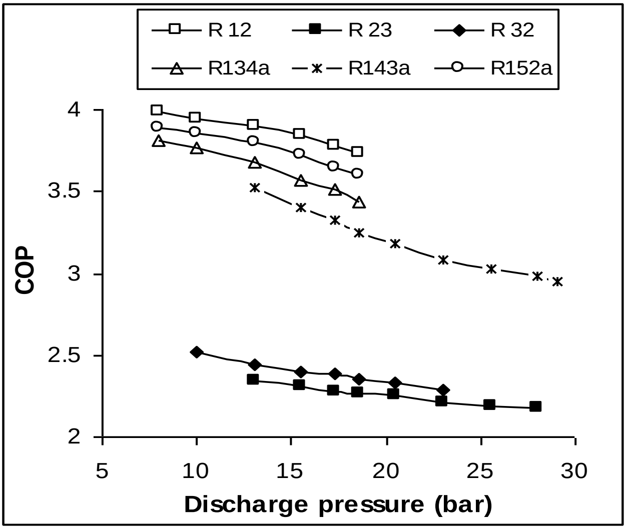


Figure 44. Variation of coefficient of performance (COP) with discharge pressure of refrigerants (Bolaji, 2010b)

Bolaji (2010c) developed another experimental test rig in the form of a household refrigerator with an evaporator compartment to carry-out further investigation on some of the selected alternative refrigerants considered in the previous test rig. The experimental refrigerator (Figure 45) consists of an evaporator, wire mesh air cooled condenser and hermetically sealed reciprocating compressor. The refrigerator was instrumented with two pressure gauges at the inlet and outlet of the compressor for measuring the suction and discharge pressure, while the energy consumption of the refrigerator was measured with watt-hour meter. The results show that the design standard set by International Standard Organisation (ISO) for small refrigerator (temperature of -3 ^{o}C and pull-down time of 150 minutes) was achieved earlier using refrigerant R152a and R134a than using R32 in the experimental refrigerator (Figure 46).

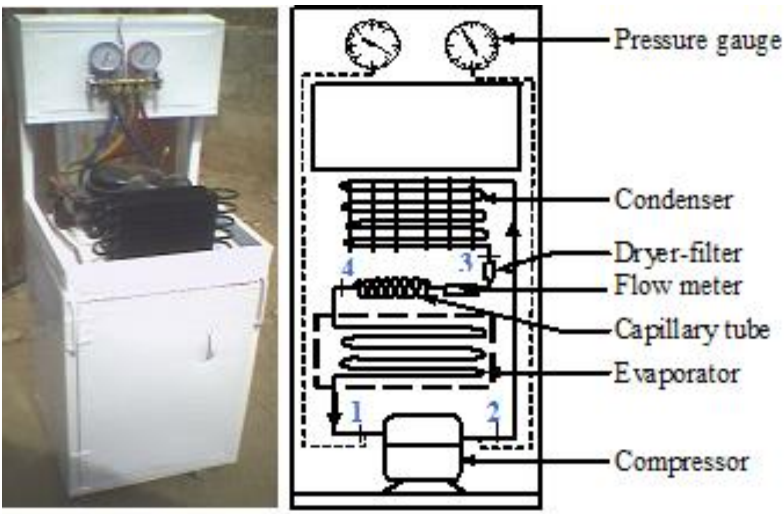


Figure 45. Experimental refrigerator (Bolaji, 2010c)

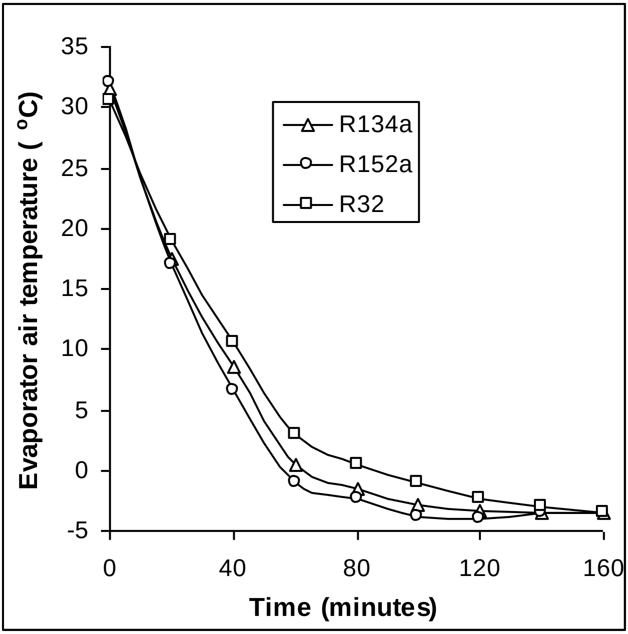


Figure 46. Pull-down time of R32, R134a and R152a in the experimental refrigerator (Bolaji, 2010c)

4.4.3 Alternative refrigerants for R12

Refrigerant 12 (R12) has been used for many decades as a working fluid in vapour compression refrigeration system. It is a very popular working fluid in home refrigerators and freezers. It was found that R12 and other chlorofluorocarbon (CFC) refrigerants destroy the stratospheric ozone layer and also contribute significantly to the world's greenhouse warming problem. In accordance with Montreal Protocol, the use of these refrigerants was prohibited all over the world in January 2010. The performance of alternative refrigerants in adiabatic capillary tube in a vapour compression refrigeration system was investigated experimentally by Bolaji (2010d). The mass flow rate was determined at a series of condensing temperatures, and at various lengths of capillary tube. The results showed that the overall heat transfer coefficient using R134a and R152a refrigerants are very close to that of R12 with only 1.6% reduction and 1.3% increase respectively (Figure 47).

Bolaji (2010e) investigated the exergetic performance of a domestic refrigerator using two environment-friendly refrigerants (R134a and R152a) as substitutes to R12 (an ozone depleting refrigerant). The results obtained showed that the average exergetic efficiencies for R134a and R152a are 13.6% lower and 4.4% higher respectively, in comparison to that of R12. The exergetic efficiencies of 41.0, 37.3 and 41.5% were obtained at evaporator temperature of -3 ^{o}C for R12, R134a, and R152a, respectively (Figure 48).

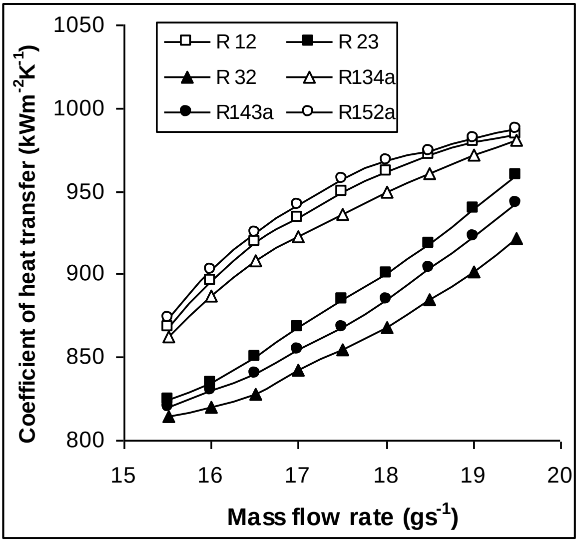


Figure 47. Overall heat transfer coefficient of some R12 alternatives (Bolaji, 2010d)

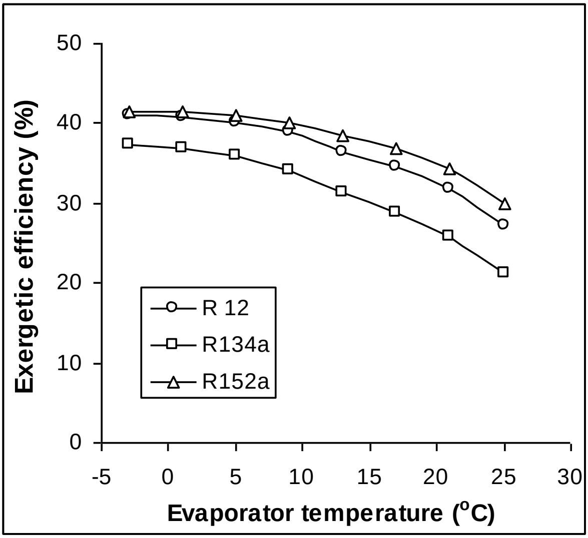


Figure 48. Exergetic efficiencies of R12 and its two alternatives (Bolaji, 2010e)

4.4.4 Alternative refrigerants for R22

Since R22 came into common use as a refrigerant in 1936, it has been applied in systems ranging from smallest window air-conditioners to the largest chillers and heat pumps. Individual equipment using this versatile refrigerant ranges from 2 kW to 33 MW in cooling capacity. No other refrigerant has achieved such a wide range of applications. However, R22 is one of a class of chemicals, HCFCs, which have been scheduled for phase out internationally by year 2030 due to the environmental hazard of ozone depletion (Bolaji *et al*., 2012). The research on refrigerant replacement for R22 has been one of dominant topics in the refrigeration and air-conditioning industry. No single-component fluid has been identified as a replacement for R22 that would meet all performance and safety requirements. In my research work, refrigerant mixtures were considered and investigated as potential replacement fluids for R22, since mixing two or more refrigerants can create a new working fluid with desired characteristics.

Bolaji (2011d) investigated the performance of R22 and its two ozone-friendly alternative refrigerant mixtures (R404A and R507) in a window air-conditioner. The performance parameters of the system using R22 were considered as benchmarks and those obtained using alternative refrigerants were compared. Experimental results showed that the highest refrigeration capacity and Coefficient of Performance (COP) were obtained using R507 in the system (Table 10). Generally, the investigation has revealed that R507 can be used successfully as a retrofitting refrigerant in existing window air-conditioners originally designed to use R22 in the event of HCFC phased out.

Table 10. Results of the performance parameters of R22 and its two alternatives (Bolaji, 2011d)

Performance parameters	**Refrigerant (Average value)**		
	R22	**R507**	**R404A**
Pressure ratio	2.22	2.38	2.93
Compressor power (kW)	1.86	1.83	1.91
Discharge temperature (^oC)	47.50	49.40	54.60
COP	2.07	2.19	1.94
Refrigeration capacity (kW)	3.86	4.01	3.71
Energy consumption (kWh/day)	1.63	1.61	1.87

Also, performances of three ozone-friendly hydro-fluorocarbon and hydrocarbon refrigerant mixtures (R413A, R417A and R422A) were investigated theoretically as alternatives to ozone depleting R22 refrigerant (Bolaji *et al*., 2015). All the three refrigerants exhibited better compressor work input than R22 as shown in Figure 49, but the best performance was obtained using R422A in the system.

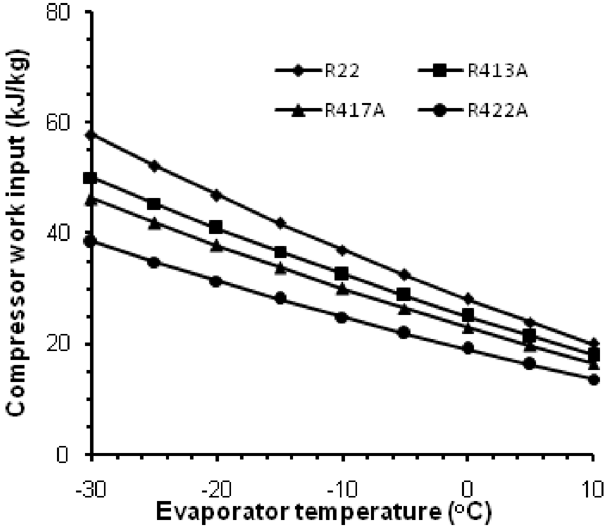


Figure 49. Compressor work input of R22 and its three alternatives (Bolaji *et al*., 2015)

4.4.5 Alternative refrigerants for R134a

R134a, a hydro-fluorocarbon (HFC) refrigerant, was first discovered as the prominent replacement refrigerant for R12, a cholorofluorocarbon (CFC) refrigerant. The thermophysical properties of R134a are very similar to those of R12. R134a is a stable, non-toxic and ozone safe refrigerant. Therefore, the refrigerant was recommended in 1989 by the American Household Appliances Manufacturers as a potential replacement for R12 in domestic refrigeration. However, while the ODP of R134a is approximately zero, its GWP of 1430 is relatively high. International concern over relatively high global warming potential of R134a has caused some European countries to abandon it as replacement refrigerant in domestic refrigerator. For this reason, the production and use of the current conventional refrigerant (R134a) will be terminated in the near future. Therefore, in my research, I carried out some studies in searching for other alternatives that are thermodynamically attractive as R134a.

Bolaji and Huan (2014) studied the performances of low global warming potential R152a, R161 and R1234yf refrigerants as alternatives to R134a in vapour compression refrigeration system. The results obtained showed that the R152a performed better than other two alternatives as R134a substitute. Also, Bolaji (2014b) investigated the performance of eco-friendly hydrofluoroolefins (R1234yf and R1234ze) and dimethyl-ether (RE170) refrigerants as substitutes for R134a in a standard vapour compression refrigeration system. The results showed that RE170 and R1234yf refrigerants exhibited very close Volumetric Refrigerating Capacity (VRC) with R134a, while the VRC of R1234ze is 26.6% low (Figure 50).

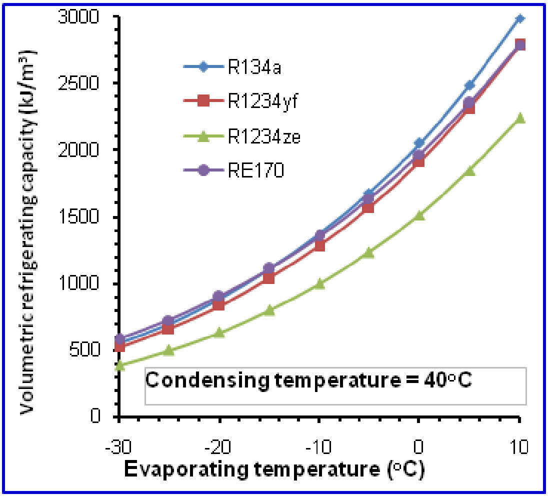


Figure 50. Volumetric refrigerating capacity of R134a and its three alternatives (Bolaji, 2014b)

4.4.6 Natural refrigerants as alternative to conventional refrigerants

The natural refrigerants are the naturally occurring substances such as ammonia, hydrocarbons, carbon dioxide, water and air. In this group, the hydrocarbons are most closely related to the HFCs. Their thermodynamic and transport properties are very similar to most HFCs currently used in refrigeration and air-conditioning systems, which make them suitable as substitute refrigerants in the existing CFC, HCFC and HFC systems. In addition to their zero ozone depletion potential (ODP) and very low global warming potential (GWP), their thermodynamic and transport properties are very similar to R134a currently used in refrigeration and air-conditioning systems.

In Bolaji and Huan (2013c), the performances of three natural refrigerants (R290, R600 and R600a) were investigated as alternatives to R134a in vapour compression refrigeration system. The results obtained showed that the saturated vapour pressure and temperature characteristic profiles for R600 and R600a are very close to that of R134a. The three hydrocarbon refrigerants exhibited very high refrigerating effect and condenser duty than R134a. The average COPs of R600 and R600a are 4.6 and 2.2% respectively higher than that of R134a. Generally, the performances of R600 and R600a in system were better than those of R134a. Oyelami and Bolaji (2015 and 2016) developed vapour compression refrigeration test rig to investigate the Performance of Liquefied Petroleum Gas (LPG) as Refrigerant (Figure 51). The LPG used for the study consists of the mixture of propane and butane in the ratio 60/40% by mass. It has zero ozone depleting potential and very low global warming potential. The results showed that the compressor power consumption of LPG was 12.5 % lower than that of R134a, while the refrigeration capacity and COP of LPG were 4.2% and 11.16% higher, respectively, than those of R134a. The system performed better with LPG than R134a.

Figure 51. Experimental LPG Refrigerator (Oyelami and Bolaji, 2016)

Bolaji and Huan (2013b) conducted performance simulation of R290 and R600a mixtures (80/20, 70/30, 60/40 and 50/50 proportion by mass) in vapour compression refrigeration system. The overall performance of the selected mixtures was better than that of R134a and the performance of the mixture with ratio 50/50 by mass was the best in terms of high Coefficient of Performance (COP) and low discharge pressure (Figure 52). Substituting Hydrofluorocarbons with natural refrigerants in domestic refrigerators will significantly reduce the direct contributions of fluorinated gases to global warming which will be of great environmental benefit. Bolaji *et al*. (2021) investigated the performance of dimethyl-ether (RE170) and its azeotropic mixtures (R510A and R511A) in a domestic refrigerator thermally insulated with its inner compartments divided into two sections, freezing and chilling as shown in Figure 53. The study revealed excellent performance of dimethyl-ether and its azeotropic mixtures in terms of higher thermal conductivity, refrigerating effect, Volumetric Cooling Capacity, COP and lower power consumption per ton of refrigeration than that of R134a in the refrigeration system.

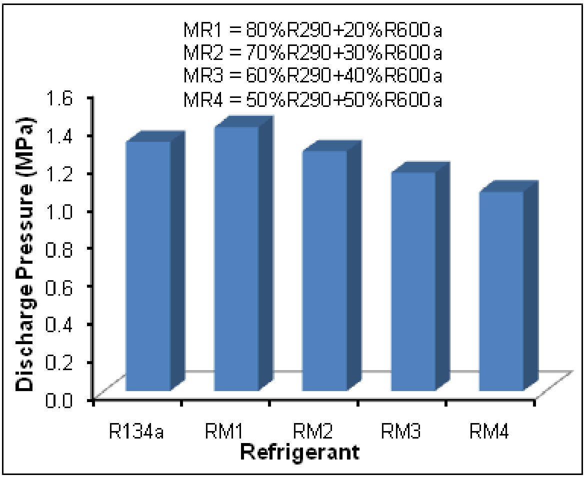


Figure 52. Discharge pressure of R134a and its alternatives mixtures (Bolaji and Huan, 2013b)

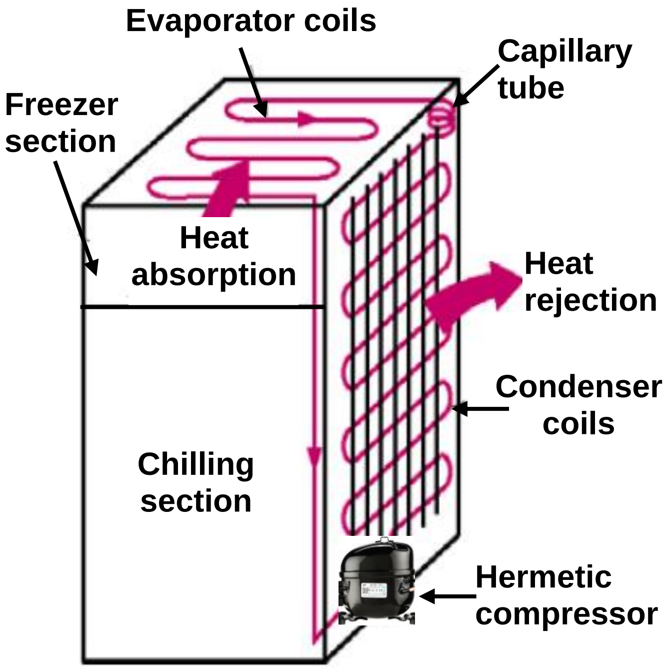


Figure 53. Schematic diagram of domestic refrigerator

4.4.7 Retrofitting the existing refrigerating systems

Retrofitting is the process of modifying an existing refrigeration system, which was designed to operate on an ozone depleting and high global warming potential refrigerant so that it can safely and effectively operate on an eco-friendly refrigerant without major effects on the performance of the equipment, and with little modifications or changes in the equipment, which will make the existing equipment to operate until the end of its economic life.

Bolaji (2012b) conducted an experimental performance study of an existing split-air-conditioner using two ozone friendly alternative refrigerants (R410A and R417A). The existing split-air-conditioner (Figure 54) originally designed for R22 as the working fluid was retrofitted with R410A and R417A respectively and the performance of the system was evaluated and compared with its performance when R22 was used. Results showed that R417A exhibited very high refrigeration capacity than both R410A and the existing CFC refrigerant (R22). Therefore, R417A will be a better choice than R410A for retrofitting existing split-air-conditioners originally designed to use R22 as working fluid.

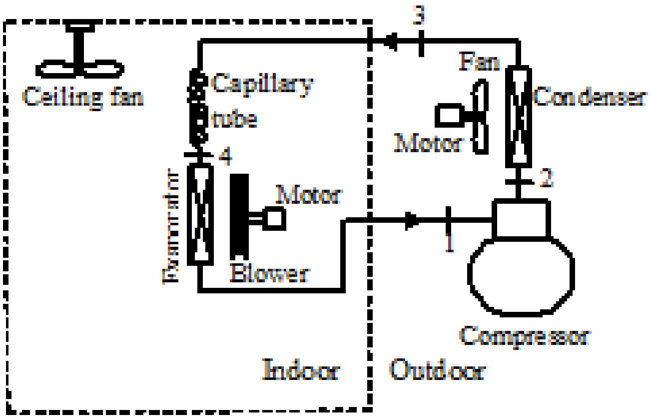


Figure 54. Schematic diagram of the experimental split-air-conditioner (Bolaji, 2012b)

Also, Borokinni, Bolaji and Ismail (2018), conducted experimental analysis of the performance of the eco-friendly R510A and R600a refrigerants in a retrofitted domestic refrigerating system and the results showed that R510A and R600a exhibited higher Coefficient of Performance (COP) and refrigerating effect than R134a (Figure 55). Therefore, they can be used as retrofit substitute refrigerants for R134a in the existing domestic refrigerators. The best performance was obtained from the use of R510A in the retrofitted system.

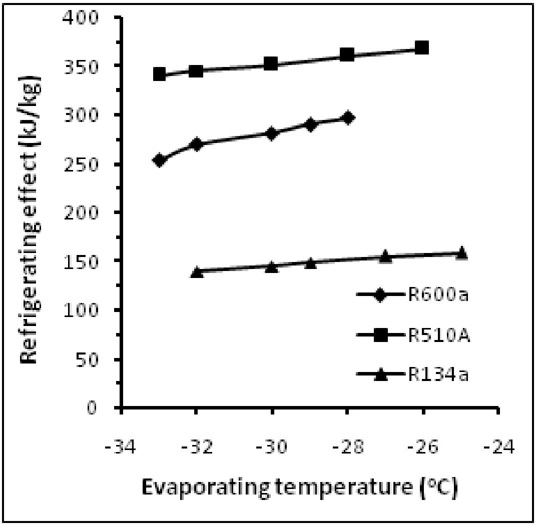


Figure 55. Refrigerating effect of R134a and its two alternatives (Borokinni et al., 2018)

4.4.8 European Union (EU) F-Gas regulations for working fluids in domestic refrigeration systems

According to European Union (EU) F-Gas Regulations, the use of refrigerants with zero ODP and low global warming potentials (GWPs) of $\leq$ 150 were mandated in domestic refrigeration systems. Table 11 shows the extract from the ban on equipment in accordance with the EU Regulation No. 517/2014. In compliance with the F-Gas Regulations, Bolaji (2020) investigated the performance of five new refrigerant mixtures (R440A, R441A, R444A, R445A and R451A) with zero ODP and GWPs of less than 150 as working fluids in domestic refrigeration systems. The results obtained showed that two of the mixtures (R440A and R451A) performed better than R134a in all the performance parameters considered, therefore, the two refrigerant mixtures can serve as long term eco-friendly substitute refrigerants for R134a in domestic refrigerators.

Table 11. Effective dates of prohibition for some of the equipment according to the EU Regulation No. 517/2014 (Bolaji, 2020)

Equipment	GWP	Effective date of ban
Domestic freezing and refrigeration systems	≥150	January 1, 2015
Small air-conditioning systems	≥150	January 1, 2020
Refrigeration plants with multi-compressors (Capacity ≥ 40 kW)	≥150	January 1, 2022
Commercial cold-rooms and refrigeration systems	≥150	January 1, 2022

4.4.9 Energy efficiency of refrigerants

Energy consumption is growing at a high speed due to rapid industrialisation and household energy consumption has become a significant feature on a global scale and it is a major factor in the current worldwide environmental problems. These have made energy optimisation a crucial issue, not only in the industrial sector, but also in the residential sector. Domestic refrigerators and freezers which are part of the main energy users in the private homes were among the first appliances targeted for energy efficiency improvements for households (Bolaji and Huan, 2012d). Energy efficiency is the major prime mover in reducing global warming (greenhouse gas emissions). Therefore, new technologies required to conserve energy, use energy effectively, use alternative energy sources and reduce the household energy running costs are under continuous development.

In Bolaji 2014a, the energy performances of low global warming potential R152a, R161 and R1234yf refrigerants were investigated as alternatives to R134a in vapour compression refrigeration system. The results obtained revealed R152a as the most energy efficient of the investigated refrigerants with average power per ton of refrigeration (PPTR) of 30.5% less than that of the conventional refrigerant, R134a (Figure 56). Bolaji *et al*. (2014b) studied the energy performance of two eco-friendly refrigerants (R152a and R600a) as alternatives to R134a in refrigeration system. Figure 57 showed the results of the variation of thermal conductivity of liquid refrigerant with saturation temperature for

R134a and its two potential alternative refrigerants. The two alternative refrigerants (R152a and R600a) exhibited higher thermal conductivity than R134a. The highest thermal conductivity was obtained using R152a. Bolaji *et al*. (2019) conducted a theoretical investigation of the energy saving potentials of three eco- friendly refrigerant mixtures (R430A, R440A and R450A) in a domestic refrigerator. The results also showed that R430A and R440A are more energy saving than both R450A and R134a in the refrigeration system. The overall best performance is obtained using R440A in the system.

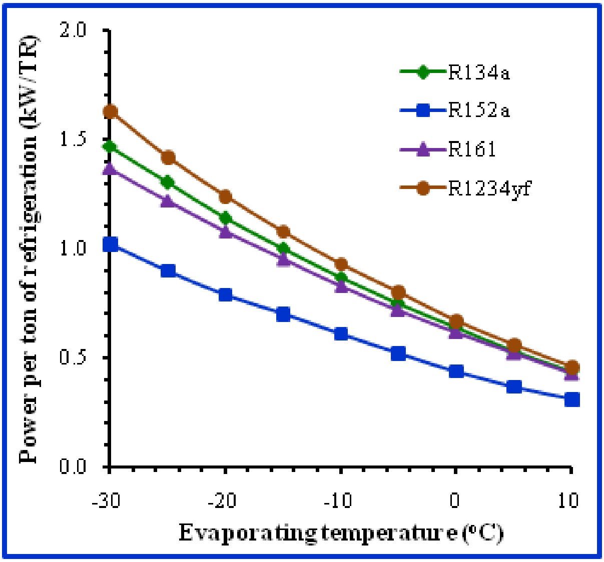


Figure 56. Power per ton of refrigeration of R134a and its three alternatives (Bolaji, 2014a)

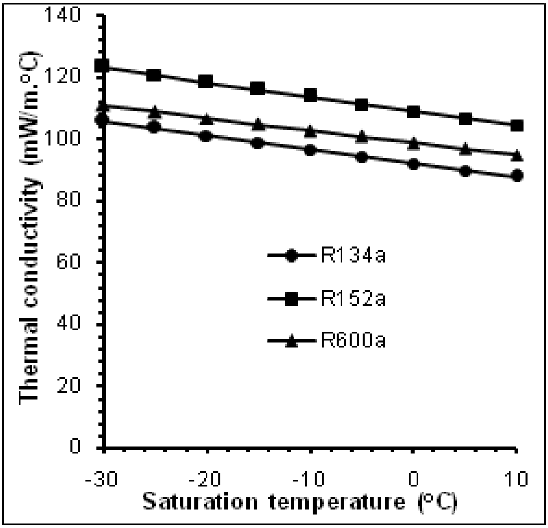


Figure 57. Thermal conductivity of R134a and its two alternatives (Bolaji *et al.*, 2014b)

4.4.10 Development of refrigeration system with sub-cooling heat exchanger

Sub-cooling heat exchangers are commonly installed in refrigeration systems with the intent of ensuring proper system operation and increasing system performance. Specifically, Bolaji *et al.* (2010a) states that sub-cooling heat exchangers are effective in:

(i) increasing the system performance;

(ii) sub-cooling liquid refrigerant to prevent flash gas formation at inlets to expansion devices; and

(iii) fully evaporating any residual liquid that may remain in the compressor suction line. Therefore, sub-cooling heat exchanger is a tool that can be used to evaluate the impact of refrigerants on refrigeration system's capacity and performance

Bolaji (2010f) presented experimental results of the effects of sub-cooling on the performance of four ozone-friendly alternative refrigerants (R32, R152a, R143a, and R134a) in a domestic refrigeration system. The study was performed using a system designed for R12 with the aim of finding drop-in replacement for the refrigerant. The schematic diagram of the refrigeration system with a sub-cooling heat exchanger is shown in Figure 58. In this system, high temperature liquid from the condenser is sub-cooled in the heat exchanger before entering the expansion device where it is being throttled to the evaporator pressure. The sub-cooling heat exchanger is an indirect liquid-to-vapour heat transfer device where high temperature and pressure liquid refrigerant transfers heat to the low temperature refrigerant vapour leaving the evaporator. The heat exchanger also prevents the carrying-over of liquid refrigerant from the evaporator to the compressor.

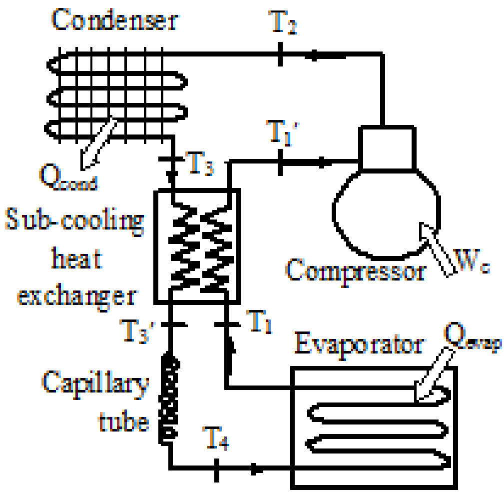


Figure 58. Refrigeration system with a sub-cooling heat exchanger (Bolaji, 2010f).

Bolaji and Huan (2013c) also conducted thermodynamic analysis of some hydrocarbon refrigerants (R290, R600 and R600a) as alternatives to R134a in a sub-cooling refrigeration system. The effects of sub-cooling on performance of the investigated refrigerants were quantified in terms of relative capacity index. The results showed increase in capacity due to sub-cooling for all refrigerants, although there were considerable variations in the magnitude of the effect of sub-cooling on the investigated refrigerants as shown in Figure 59. The highest RCI was obtained using R600 with 14.6% higher deviation from that of R134a, while R290 produced the lowest RCI with 17.4% lower deviation from that of R134a. The performances of R600 and R600a in system were better than those of R134a and R290.

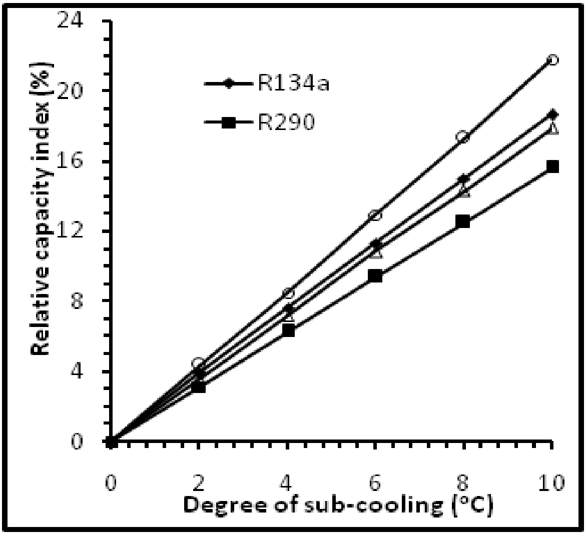
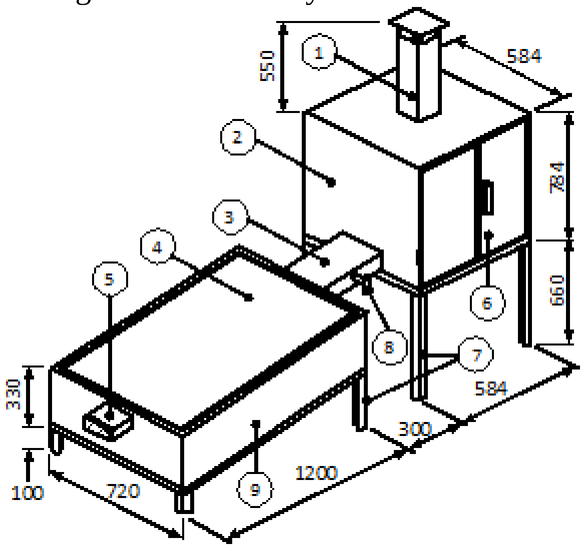


Figure 59. Variation of relative capacity index (RCI) with degree of sub-cooling. Bolaji and Huan, 2013c)

4.5 Machine Design and Fabrication

4.5.1 Development of a solar poultry egg incubator

Incubation is an art of managing fertilized eggs to ensure the satisfactory development of embryo into a normal chick either by natural or artificial method. The egg is an extremely specialized structure which contains sufficient food and water to develop a fertilized cell into a chick if subjected to adequate environmental conditions. The environmental factors of major importance for artificial incubator include temperature, relative humidity, air supply and egg turning. These four parameters must be properly monitored during incubation. Simple and relatively cheap artificial incubators that are independent of conventional energies are favoured for the increase in production of chicks and protein intake in developing countries. Therefore, in Bolaji 2008a, a solar poultry egg incubator was designed and fabricated using locally sourced materials to make it relatively affordable to the average poor farmer dwelling in the rural area. The solar poultry egg incubator is shown in Figure 60. The equipment consists of a solar collector with built-in thermal storage unit, air ducts, incubating unit and chimney.



All dimensions in mm. (1) Chimney, (2) Incubating cabinet, (3) Air outlet duct, (4) Transparent glass cover, (5) Air inlet duct, (6) Cabinet door, (7) Stands, (8) Air flow regulator and (9) Solar collector.
Figure 60. Solar poultry egg incubator (Bolaji, 2008a).

4.5.2 Development of drinking water filters

Safe drinking water is not available to the majority of the people living in the developing countries. Unsafe drinking water, combined with insufficient water supply for sanitation and hygiene, is responsible for an estimated 4 billion cases of diarrhoeal disease and about 2 million diarrhoea deaths. Even water treated with a disinfectant often becomes contaminated when collected from a public standpipe and stored at home. The methods used to treat water and make it safe for drinking must be accessible and affordable to all, as well as culturally and environmentally acceptable. These methods are of two kinds; (i) method used by the municipal authorities at central points from where water is distributed, and (ii) method used in individual homes. Because large water infrastructure systems are unavailable in many developing countries, household water treatment and safe storage (HWTS) systems offer good intermediate solutions. Hence, household water treatment technology must be technically effective, inexpensive, easy to use, locally made, and socially acceptable.

Bolaji *et al.* (2010b) carried out design and construction of a domestic drinking water filter using locally available materials as shown in Figures 61 and 62. The filter was composed of materials that can remove odour, colour, taste, turbidity, and other objectionable materials from water. The filter was tested with water samples collected from various sources in Akure, Nigeria and water quality parameters were monitored before and after filtration. Also, in Bolaji and Akande 2013, a ceramic filter for point-of-use water purification was designed, fabricated and tested to evaluate its performance in filtering water to the World Health Organisation (WHO) standards. The results of pH of water samples obtained after filtration ranged from 7.68 to 8.11 (Table 12). Comparison of the results with the WHO standards for drinking water showed that the ceramic water filter can provide potable drinking water of required standards.

Figure 61: Domestic water filter (Bolaji *et al*., 2010b).

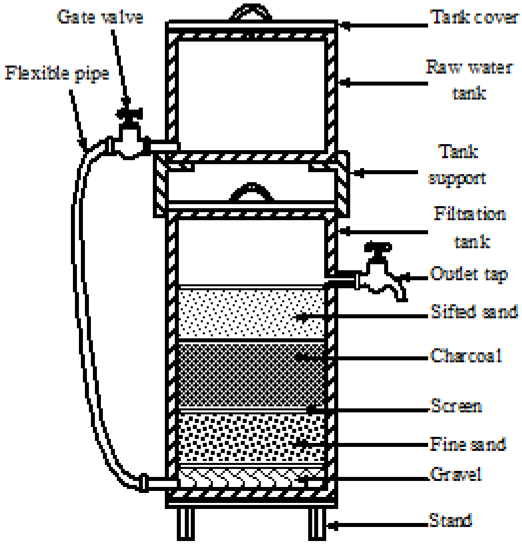


Figure 62. Sectional view of the domestic water filter (Bolaji *et al*., 2010b).

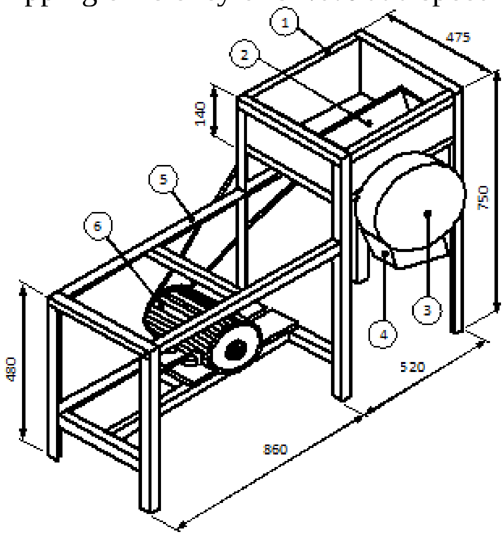
Table 12: The pH of water samples (Bolaji and Akande, 2013)

Water source	pH	
	Before filtration	After filtration
Well	7.47	7.68
Rain	7.76	8.07
River	7.71	7.85
Borehole	7.80	8.11

4.5.3 Development of food processing machines

One of the ways to improve agricultural mechanization in Nigeria is the encouragement of indigenous design, development and manufacture of most of the required machines and equipment, this is to ensure their compatibility and sustainability for the farm produce as well as the incorporation of farmers technical and financial consideration (Adejuyigbe and Bolaji, 2005; Martins *et al*., 2018). The increase in the production of root crops in Nigeria has brought about the need for the development of appropriate processing technology. Presently, cassava is one of the most important root crops in Nigeria. Cassava tubers once detached from the growing plant will normally not stay for more than three to four days without being processed in some way, before deterioration sets in. Therefore, there is an ever-increasing need to quickly process cassava tubers in some stable forms as soon as it is harvested.

A very important and vital step in processing cassava is the reduction of the peeled fresh roots into smaller sizes by slicing or chipping. In the traditional method of cassava chipping, knives and machetes are used mechanically to reduce peeled cassava to small sizes. Therefore, it is necessary to mechanize the chipping process in order to overcome the difficulties of handling large scale processing with the traditional method since chipping operation alone will create a bottleneck. Bolaji *et al.* (2008c) designed and constructed a cassava chipping machine using locally sourced materials with the aim to increase the rate of processing cassava tubers into some stable forms as soon as it is harvested (Figure 63). The performance of the machine was also evaluated and the results showed that the machine has a maximum capacity of 245 kg/h at 500 rpm and maximum chipping efficiency of 92.6% at a speed of 300 rpm.



All dimensions in mm. (1) Hopper, (2) Feeding chute, (3) Chipping unit, (4) Discharge chute, (5) Machine frame, and (6) Electric motor.

Figure 63. Cassava chipping machine (Bolaji *et al.*, 2008c).

Also, the importance of rice as a staple food in Nigeria has risen dramatically in the last four decades. Today, rice is hawked on the street of all cities and villages in the country and for many families; it is a daily item on the menu. Hence, any research on the improvement of the locally produced rice is not misdirected. Reasonable quantities of rice are produced yearly from different rice fields in Nigeria, but many Nigerians prefer imported rice. This is partly attributed to the fact that about 80% of rice produced locally in Nigeria contains stones. This is so, because most of rice produced locally is processed manually or with inefficient methods. The greater part of stones in Nigeria rice is introduced during winnowing, drying and milling. Therefore, in order to remove stones and other impurities from the locally produced rice, Adejuyigbe and Bolaji (2012) designed and fabricated a rice de-stoning machine with vibrating sieves using locally sourced materials (Figure 64). The performance of the machine was evaluated and the average capacity of the machine was found to be 31.84 g/s while the average de-stoning efficiency was 98.3%.

Figure 64. Rice de-stoning machine (Adejuyigbe and Bolaji, 2012)

4.6 Development of Laboratory Apparatus

My Vice-Chancellor Sir, Distinguished Scholars, Ladies and gentlemen, I have also contributed in the area of improvising experimental apparatus to enhance research, teaching and learning of Thermo-fluids. The study of fluid flow is one of the few areas of engineering that truly crosses the boundaries between the various engineering disciplines. An ideal flow is a purely theoretical concept; as such flows pose no viscosity, compressibility, surface tension or vaporization pressure limit. However, the mathematical treatment of such flow was fundamental in the development of aerofoil lift, fan and pump blade design and ground water flow predictions.

The study of fluid flow phenomenon is a very important one in the education of engineering students and one of the equipment that can help in doing this is the forced vortex equipment. Oladebeye and Bolaji (2004) designed, constructed and carried out performance test of a forced vortex equipment for use in the fluid mechanics laboratory to carry out students' practical tests in relation to fluid rotation. The equipment (Figure 65) operates on the principle of using mechanical means to impart motion to the fluid in a cylinder. The motion results in pressure head variation from one stream line to another. Due to this variation in pressure head, fluids develop a parabolic shape at its head. The experimental results are therefore used to verify the concept of turbulence in fluid flow. The results obtained showed a parabolic profile of liquid surface in the equipment, which confirmed the type of equation of pressure head normally developed in a forced vortex.

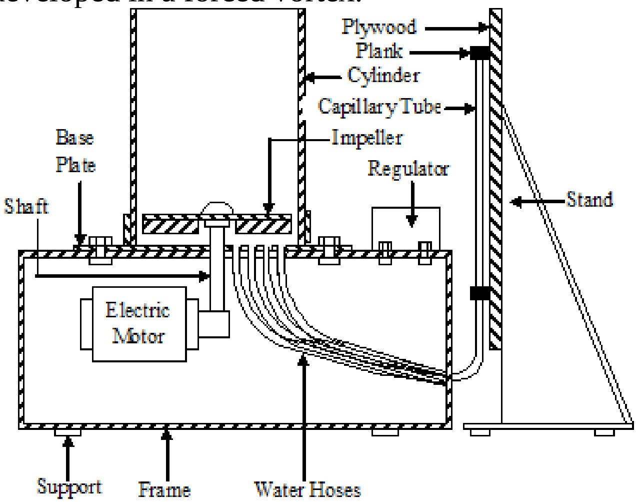


Figure 65. Forced vortex equipment (Oladebeye and Bolaji, 2004).

Furthermore, an experimental apparatus that will enhance the teaching and learning of thermodynamics is needed in various institution of higher learning. Through practical demonstration of refrigeration system, students would be able to apply thermodynamics principles, such as the first and second laws, learned in the classroom lectures, to real-life problems. Bolaji and Falade (2012) designed, constructed and carried out performance test of an apparatus for use in the thermodynamics laboratory to demonstrate vapour compression refrigeration system and to carry out students' practical tests in relation to thermodynamics principles (Figure 66).

Figure 66. Apparatus for demonstrating vapour compression refrigeration system
(Bolaji and Falade, 2012).

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Global environmental problems are becoming increasingly significant as fossil fuels consumption is growing at a high speed due to technology advancement and rapid industrialisation. Carbon dioxide (CO_2) is produced when fossil fuels are burned; causing an increase in the concentration of atmospheric CO_2 and increase in the earth's temperature (global warming) through green-house gas effect. The emission of polluting substances and global climate change has all made energy optimisation a crucial issue, not only in the industrial sector, but also in the residential sector. Achieving solutions to the global environmental problems that humanity faces today requires long term potential actions for sustainable development. In this respect, this lecture has shown that renewable energy systems have potential of providing the lasting solution to the problem of environmental pollution and global warming. This can be realized by decreasing pollutant emissions through the replacement of fossil fuels with renewable energies as demonstrated by the various renewable energy technologies and machines developed.

In spite of the inherent advantages of refrigeration and air-conditioning, they have contributed significantly to the two major global environmental problems (ozone layer depletion and global warming) through the release of anthropogenic chemicals (refrigerants) into the atmosphere. This lecture has also presented natural refrigerants as the ideal refrigerants and the ultimate solution to the problems of ozone depletion and global warming. The potentials of various natural and environment-friendly refrigerants and their areas of application in refrigeration and air-conditioning systems were analysed which have provided strong basis for the need to embrace the use of natural refrigerants as replacement for the conventional halocarbon refrigerants.

5.2 Recommendation

My Vice-Chancellor Sir, Distinguished Scholars, Ladies and gentlemen, while showing great appreciation for the valuable time you have all sacrificed for this lecture, I have the following recommendations for government, relevant agencies, corporate bodies and institutions not only in Nigeria but also across the globe since the lecture focused on global problems;

(a) Natural refrigerants should be considered as the main alternative working fluids in refrigeration and air-conditioning systems since this is the only well-known sustainable mitigation strategy for climate change contributions by the refrigeration industries.

(b) Electricity is a clean energy carrier, but to a large extent, coal, oil and gas are burned to produce it. Therefore:

    (i) The emphasis in the power generation sector should be on cleaner production methods by making use of alternative sources of production of electricity such as wind, solar, hydro and bio-energy.

    (ii) The thermal stations which depend on burning of fossil fuels and emission of carbon-dioxide should be gradually faced out.

    These recommendations are needed to meet future electricity demand in a way that global warming will be totally eradicated which will be in line with sustainable development objectives.

(c) Government should subsidize renewable (clean) energy, make it more affordable and cost-competitive with fossil fuels.

(d) Government should come out with policies that will effectively, efficiently and rapidly increase renewable energy deployment. Renewable energy deployment can be accelerated if regulatory and incentive-based policies are put in place.

(e) Government should establish clear, consistent and achievable targets for renewable energy development and environmental stewardship.

(f) Conducive environments should be created for public-private partnerships in clean energy development. Private sector engagement will accelerate energy development by mitigating public finance shortfalls and encouraging deployment of renewable energy technologies.

(g) International cooperation and support for developing countries should be enhanced towards the expansion of infrastructure and upgrading technology for modern supply and sustainable energy services as a way of mitigating climate change and its impacts.

(h) Global emissions management system should be instituted in which countries will receive price for their low carbon and potential future clean energy contribution.

(i) Future research should be on the development of a battery that can store gobs of energy for months or years, a solar panel that is twice as efficient, and a crop that produces biofuels cheaper than petroleum.

(j) Countries that depend exclusively on fossil fuels as the source of their income should urgently search for other alternatives because of the imminent prohibition of the use of fossil fuels.

If these recommendations are implemented, the involvement in human (anthropogenic) emissions of greenhouse gases and other environmentally unfriendly refrigerants will be totally cut-off, and the magnitude or rate of long-term global warming and its related effects will be drastically reduced if not totally eliminated. Also, implementation of these suggestions will guarantee the sustainability of renewable energy resources and access to affordable, reliable, sustainable, modern energy for all and combat climate change and its impact.

6. ACKNOWLEDGEMENTS

My Vice-Chancellor Sir, Distinguished Scholars, Ladies and gentlemen, I hate to disappoint you, but I do not belong to the elite class of "self-made men". Rather, I am a "God-made man", a product of grace; absolute grace. I owe much first of all to the Almighty God, creator of Heaven and Earth who chose in Christ Jesus to adopt me as his son and opted to be my Shepherd, Master and friend. I give Him all praises, Glory and Honour for His protection, preservation, provision, loving kindness, tender mercies, abiding presence and guidance over me which has kept me safe and alive to stand before you today, regardless of the activities of the devil and his human agents.

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BIODATA OF PROFESSOR BUKOLA OLALEKAN BOLAJI

Professor Bukola Olalekan Bolaji was born on February 26, 1964. He is the fourth child of Late Madam Victoria Bolaji, the 6th wife of Late Chief Samuel Mobolaji Ojoodide, the Basorun of Okemesi-Ekiti. He commenced his educational carrier at Saint Michael Anglican Primary School Okemesi-Ekiti (1969 to 1975). He attended Saint Stephen Secondary Modern School, Okemesi-Ekiti, from 1975 to 1978. He also attended both Babatope Memorial High School, Ikoro-Ekiti where he received the award of best student in Mathematics from 1978 to 1981, and Okemesi Grammar School, Okemesi-Ekiti, from 1981 to 1983.

After his secondary school education, he worked as a Store-keeper at the Nigerian Carton and Packaging Company (NICAPACO), Ilupeju, Lagos. In 1985, he proceeded to Lagos State Polytechnic for his National Diploma Certificate, where he graduated as the best student in Mechanical Engineering at National Diploma level. He also worked as a Technician in three different companies after his National Diploma (M.A. Kay Technical Company, Isolo Road, Mushin, Lagos; MicCom Cables and Wires Limited, Lagos; and Peerless Technology Nigeria Limited, Lagos). He proceeded to the Federal University of Technology, Akure, Ondo State, where he had his B.Eng., M.Eng. and Ph.D degrees in Mechanical Engineering in 1993, 1997 and 2008, respectively. His deep interest in the study of environment-friendly refrigeration system won him a Post-doctoral Fellowship at the Tshwane University of Technology, Pretoria, South Africa in 2011. And in August 2013, he was given the award of Academic Excellence by the same University as the best Post-doctoral Fellow of the year 2012.

Professor Bolaji has worked in various schools and institutions. He served as Class Teacher in Ise-Emure Grammar School, Ekiti State in 1993, Akure Academy Secondary School from 1993 to 1994 and in Omoluorogbo Grammar School, Akure from 1994 to 1995. He lectured for about nine years (1995 – 2004) at the Federal Polytechnic, Ado-Ekiti. Also in January 2004, he joined the service of the Federal University of Technology, Akure as Lecturer II. In January 2006, he was appointed as Lecturer I at the Federal University of Agriculture, Abeokuta where he rose to the position of Associate Professor in 2012. And in July 1, 2014, he was appointed as a full Professor in the Department of Mechanical and Mechatronics Engineering, Federal University Oye-Ekiti.

Professor Bolaji served in various capacities in all the tertiary institutions where he has worked. He was a member, School of Engineering Research and Publication Committee, Federal Polytechnic, Ado-Ekiti (1999 - 2003); member, School of Engineering Examination and Time-Table Committee, FUTA (2004 – 2006); member, School of Engineering Publications and Curriculum Development Committees, FUTA (2004 - 2006); member, Anti-Corruption and Transparency Monitoring Unit (ACTU), FUNAAB (2010 – 2014); member, University Committee on the Review of Procedure of Processing Academic Transcripts, FUNAAB (2009); member, University Committee on the Development of a New Programme for Processing of Results, FUNAAB (2010); member, University Committee on Alternative Electricity Generation for FUNAAB (2010 – 2011); member, University Time-Table and Examination Committee (TIMTEC), FUNAAB (2009 – 2011); member, University Publication Committee, FUNAAB (2008 – 2014); member Users Committee for the Construction of 2,000 Capacity Lecture Theatre, FUNAAB (2010 – 2011). He was also the Departmental Examination Officer at Federal Polytechnic Ado-Ekiti in 2001 – 2004, at FUTA in 2004 – 2006, and at FUNAAB in 2006 – 2010; Chairman COREN and NUC Accreditations Committee, College of Engineering, FUNAAB (2006 – 2010); Vice-Chairman, Management Committee on Transportation (MANCOT), FUNAAB (2009 – 2011); member, FUOYE Senate Ad-hoc Committee on the Review of Guideline for Appraisals, Appointments and Promotions of Academic Staff (2015); Senate Representative on the Appointments and Promotions Committee of Council, FUOYE (2018 to 2022); member, Search Committee for the Appointment of Vice-Chancellor, FUOYE (2020); Coordinator, Department of Mechanical Engineering, FUNAAB (2007 – 2008); Ag. HOD, Mechanical Engineering, FUNAAB (2010 – 2011); Pioneer HOD, Mechatronics Engineering, FUNAAB (2012 – 2014); HOD, Mechanical Engineering, FUOYE (2015 – 2016); Director, ICT Unit, FUOYE (2016

– 2017); Chairman, Technical Board of ICT Directorate, FUOYE (2021 to date); and currently, he is the Dean, Faculty of Engineering, FUOYE.

Prof. Bolaji has served as member, and has the Team Leader of NUC accreditation teams to many universities in Nigeria. He has also served as an external examiner to many universities within and outside Nigeria, and as a reviewer to many International Journals. He is a registered Engineer and a member of several professional bodies, including: the Nigerian Society of Engineers, Environment and Behaviour Association of Nigeria, Nigeria Institution of Engineering Management, Southern African Association of Energy Efficiency, and United Nations-African International Partnership for Sustainable Development Goals.

Prof. Bolaji received the Vice-Chancellor Award as the most Innovative Lecturer in the Faculty of Engineering, Federal University Oye-Ekiti in 2021. He has also received several research grants, including Research Grant RG202 (award of ₦200,000.00 in 2006) from the Federal University of Agriculture, Abeokuta; and Research Grant IRG01 (award of ₦350,000.00 in 2008) from the Institute of Food Security, Environmental Resources and Agricultural Research to carry out a research on “Design and Construction of a Solar Photovoltaic Powered Refrigerator for Rural Applications”.

Prof. Bolaji has supervised and co-supervised about 32 Master degrees and 9 Ph.D degree students. Two of the students he supervised are now full Professors and four are Associate Professors. He has more than 150 academic publications and 51 of his articles are indexed in SCOPUS.

Prof. Bolaji also involves in other extra curriculum activities. He is currently a District Pastor in Deeper Life Bible Church. He has also served as Coordinator and Pastor in various arms of Deeper Christian Life Ministry, including Children, Youth and Campus Ministries. He his happily married to Mrs. Veronica Oluyemisi Bolaji and the marriage is blessed with three beautiful, obedient and God-fearing daughters.