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Energy Storage Technologies

I- INTRODUCTION

Energy is the measure of the economic and social development, and is basis for the progress and prosperity of nations and societies. Energy storage systems can be classified in different ways as the following:

- According to the type of energy stored e.g. thermal, chemical, mechanical, etc.
- According to the stage of development of the technology, e.g. pumped-water storage,
- According to the period of storage, long-term or short-term,
- According to the temperature requirements; low, moderate and high temperature,
- According to the nature of the source used e.g. traditional, renewable.

The present review article focuses on the new technologies for energy storage systems and some of applications. The main goals are to develop energy storage, improve efficiency, behavior, performance, design and reduce costs effective for energy storage systems.

2- STORAGE OF PRIMARY ENERGY

Primary energy resources is conventional resources e.g. coal, petroleum oil and natural gas, etc.

2-1 Coal Storage

Two types of coal storage are used; coal storage pile and reserve storage. Coal storage piles, at any point of the coal cycle, have a number of environmental impacts e.g. coal dust is the most common air pollutant.

2-2 Crude Oil and Rfined Products Storage

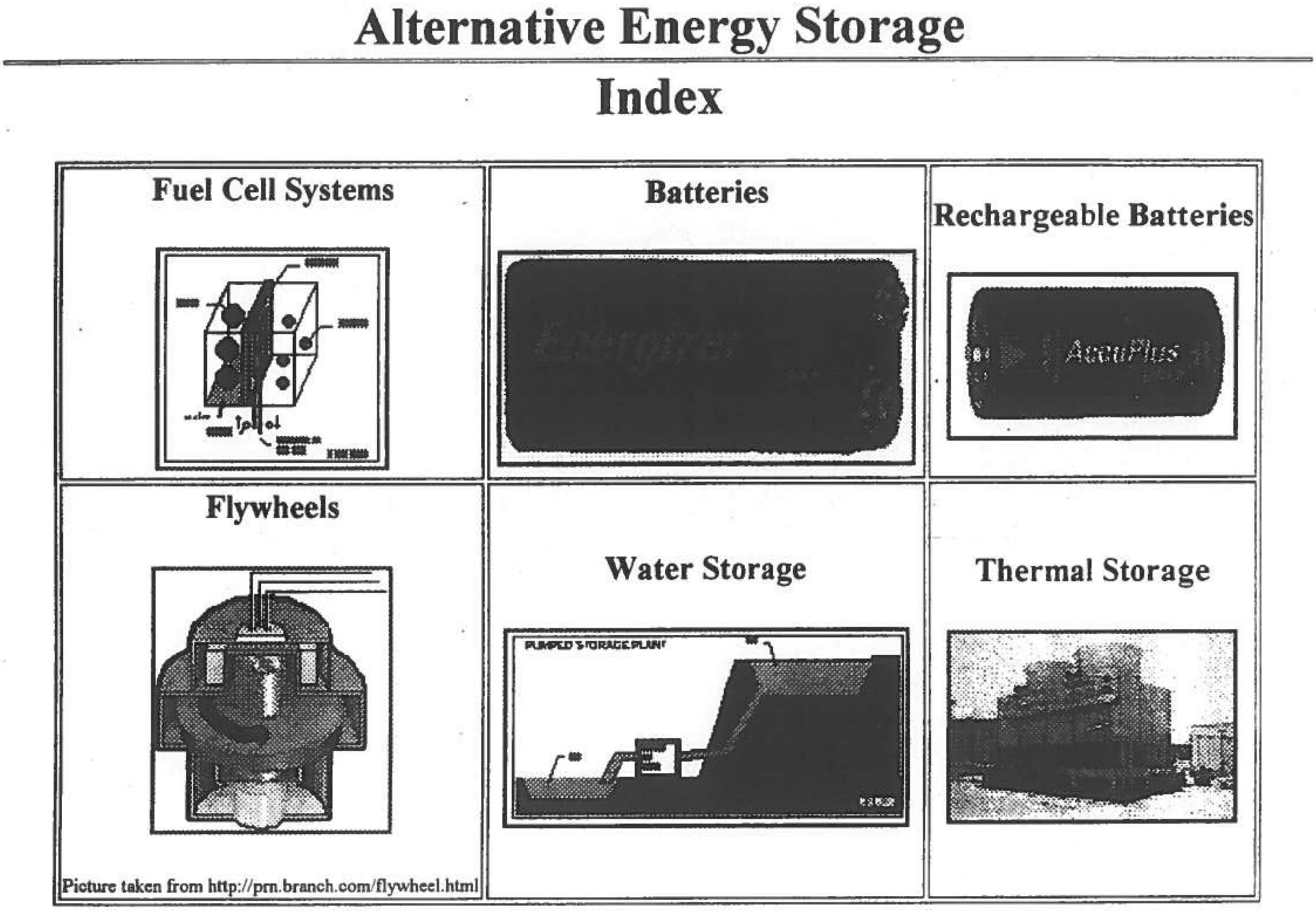
Large tanks are used to store crude oil and refinery products prior to transport or use. The tanks may be located at production sites, pipelines, terminals, refineries, tank farms, or usage locations. The tanks basically consist of a cylindrical steel shell topped by hemispherical roof and equipped with a pressure/vacuum vent designed to minimize pressure-induced outflows of Hydro-Carbon-Laden vaporous and inflows of air. Numerous mechanical safeguards and operating procedures are employed within the oil industry to maximize safety in the event human error, fire, and explosions. Several countries use underground storage to provide a "strategic" stockpile, to realize the safety problems (fire and explosions) during the filling operations.

2-3 Natural Gas Storage

Natural gas is normally stored underground in depleted gas reservoirs, and depleted oil reservoirs are also used. In most underground reservoirs, water present in porous media is the confining medium; the stored gas tends to form a "bubbles", [1]. Gases are stored under pressure, from several hundred to several thousand pounds per square inch. Leak from valves, flanges, compressors, well heads and joints are inevitable. Gas storage reservoirs normally have operational lifetime of 30 to 50 years or more.

3- ELECTRIC STORAGE TECHNOLOGIES

The electrochemical batteries are widely used since the battery technology is known than that of the others. There are number of energy storage technologies have been developed or are under development for electric power applications. Alternative energy storage index of the electric energy storage technologies is shown in Fig. (1).



Picture taken from http://prn.branch.com/flywheel.html

Fig. 1 Alternative energy storage types.

3-1 Flywheel Storage

A flywheel is an electromechanical device that couples a motor/generator with a rotating mass to store energy for short duration. Conventional flywheels are "charging" and "discharging" via an integral motor/generator. The motor/generator draws power provides grid to spin the rotor of the flywheel. During a power outage, voltage sag, or other disturbance, the motor/generator provides power. Kinetic energy stored in the rotor is transformed to DC electric energy by the generator. Several researches have focused on the development of materials with high working strength-density ratios. Advanced flywheels (rotors) constructed from Carbon-Fiber materials and magnetic bearing can spin in vacuum at speeds up to 40, 000 RPM, [2]. Development of flywheel for utilities has been focused on the power quality applications, [3]. Advances in flywheel energy-storage systems are presented by Bryan et al. [4]. They made a few modifications to the design of the traditional flywheel; a)- by inserting a rectifier after the generator, the system is capable of delivering approximately 75 % of the flywheel's energy as usable DC power. The DC power must be filtered and inverted back to AC power at 60 Hz, b)- adding a variable-speed drive (VSD) to the system allows efficient motoring of a large inertia from lower rotational speeds, enabling a smaller motor to be used for this standby power source. Figure (2) shows the traditional integration of a steel flywheel with a motor/generator set, and Fig. (3) shows the system with variable-speed drive and rectification/inversion electronics.

Basic characteristics of the flywheel:

The kinetic energy, E, stored in the flywheel is

$$E = 1/2\ (I\ \omega^2) \qquad (1)$$

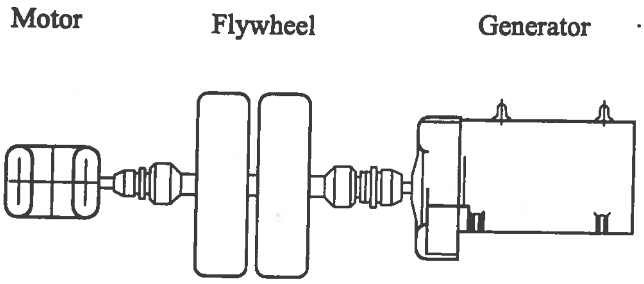


Fig.(2) Traditional integration of a steel flywheel with a motor/generator set.

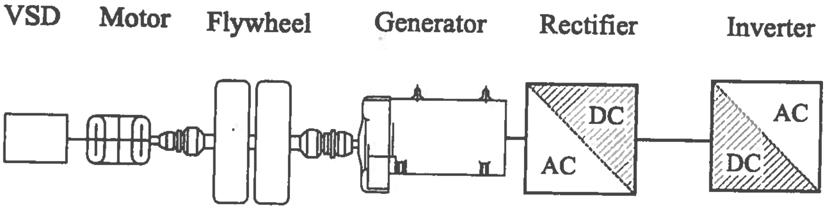


Fig.(3) System with variable-speed drive and rectification/inversion electronics.

Where I is the moment of inertia about the rotational axis of the flywheel and depends on the shape of the flywheel, and ω is the angular velocity.

$$I = k\,m\,r^2 \qquad (2)$$

Where k is inertial constant, m and r are the mass and radius of the flywheel, respectively.

3-2 Compressed Air Energy Storage (CAES):

CAES systems use off-peak to compress and store air in air-tight underground caverns. When the air is released from storage, it expands through a combustion turbine to create electricity, [5]. Air can be stored in pressurized tanks for small systems. The performance characteristics of **CAES** systems have been discussed and investigated by Decher and Davis, [6]. In their work, they have presented a mathematical model for the system shown in Fig. (4).

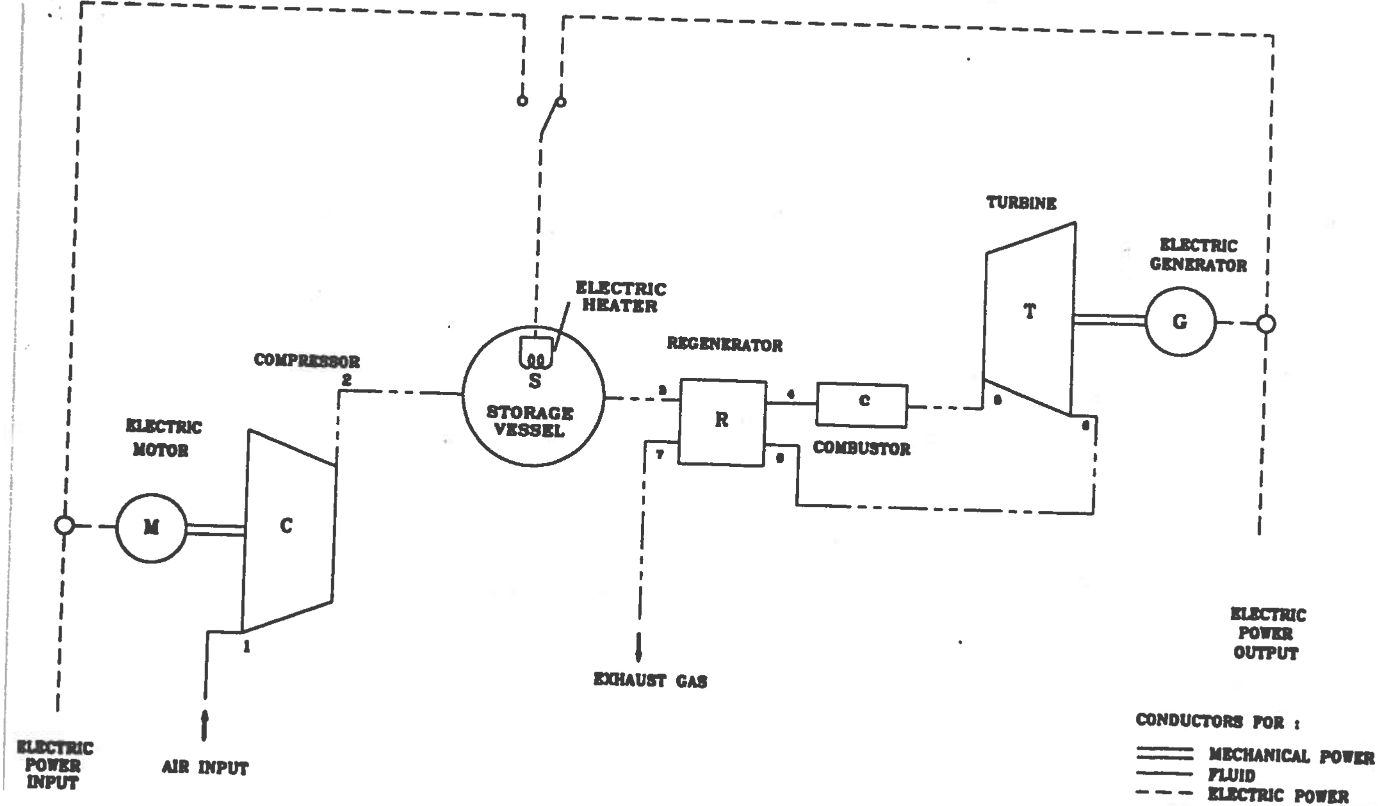


Fig. 4 A general compressed air energy storage system.

CAES is suitable for use with wind-energy systems. Investigation [7] presents a system, which consists of wind turbine, compressor, storage tank, and air-lift pump, the assembly of this system is shown in Fig. (5). The output power and capacity were determined and the characteristics of air-lift pump were studied by using a numerical model.

3-3 Pumped Hydropower

Pumped hydro facilities are used during off-peak electricity to pump water from a lower reservoir into the other one at a higher elevation where it can be stored as potential energy. When the water stored in the upper reservoir is released, it down flow passes through hydraulic turbines to generate electrical energy. The increase in elevation represents an increase in the gravitational potential energy, W (kilowatt~~s/~~hour), of water: ρ is the water density (1000 kg/m^3), V is the water volume (m^3), g is the gravitational constant (9.8 m/s^2), and ΔZ is the change in elevation (m). The following equation is used to evaluate the kilowatt~~/~~hour for the pumped hydro storage, [8]:

$$W = \rho V g \Delta Z / 3.6\ 10^6 \qquad KWH \qquad (3)$$

Figure (6) is the illustration of the pumped hydropower energy storage system. Normally this kind of system is for large-scale utility use and the efficiency is about 60 % to 70 %, [9].

3-4 Fuel-Cells

Fuel cells are devices that convert chemical energy directly into electricity without combustion. Hydrogen and oxygen are produced using electrolyser, which are stored in tanks. The fuel-cell then use the electrochemical reaction of these two gases (H_2 & O_2) at the separate electrodes to generate electricity during peak load or when there is extra

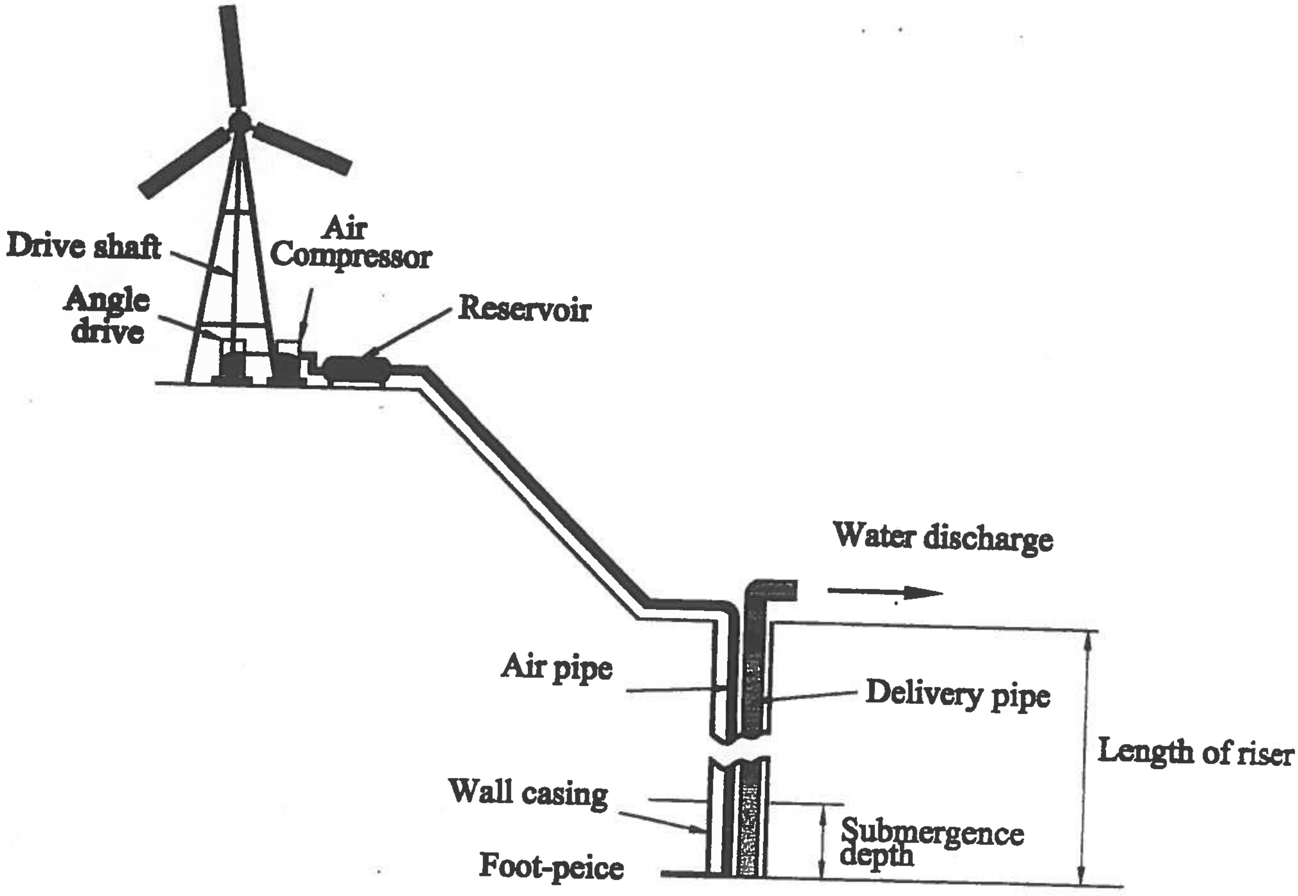


Fig. 5 Assembly of the wind turbine-compressed air storage system

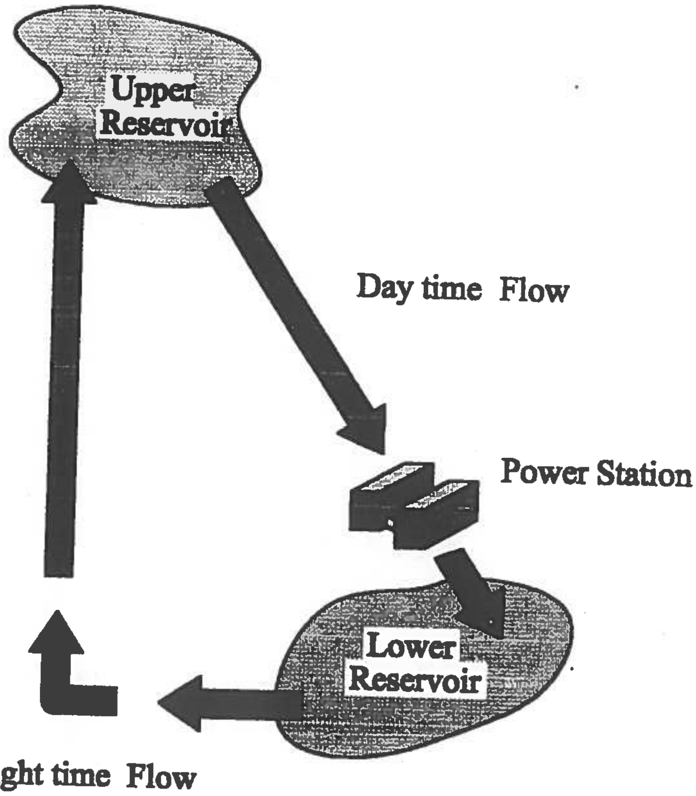


Fig. 6 Illustration of pumped hydropower energy storage system

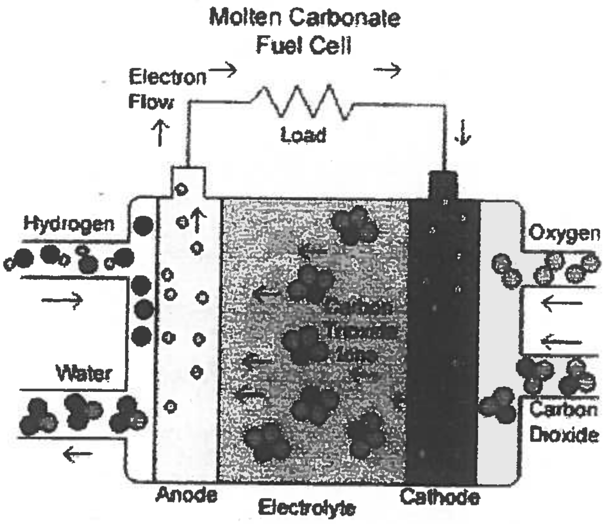
need, [10] The only product during electricity generation is water and heat, so is a clean source. There are different types of fuel cells including phosphoric acid, alkaline, molten carbonate, solid oxide and proton exchange membrane (MEM) fuel cells. Several types of fuel cells have been developed or under development. These fuel cells are classified according to the kind of electrolyte. The configuration and description of five types of fuel cells that widely used are given in Table (1), [11]. Analysis of Molten Carbonate Fuel Cell (MCFC) power-generation systems using dynamic simulation is presented [12]. MCFC involves the oxidation of a fuel and the reduction of an oxidant. The electrons pass from the fuel electrode to the oxidant electrode via an external circuit, and the electrical circuit is completed by ionized particles crossing an electrolyte. MCFC power-generation system consists of four major parts as follows;

1-fuel processing (converting fuel to gas with high concentrations of hydrogen and monoxide).
2-fuel-cell power-generation (using gas with a high concentration of hydrogen, carbon monoxide and air to generate DC electricity).
3-Power conversion (converting electricity from DC to AC).
4-Heat recovery co-generation (utilizing the excess heat).

Alternative fuel flow control with normal or high temperature and drawing of Molten Carbonate fuel cell are shown in Fig. (7).

3-5 Batteries Storage

In recent year, much focus in the development of electric energy technology has been centered on battery storage devices. In chemical battery, charging causes reactions in electrochemical compounds to store energy from a generator in a chemical form. Upon demand, reverse chemical battery and back to the grid. Batteries increase power quality and



Drawing of molten carbonate fuel cell

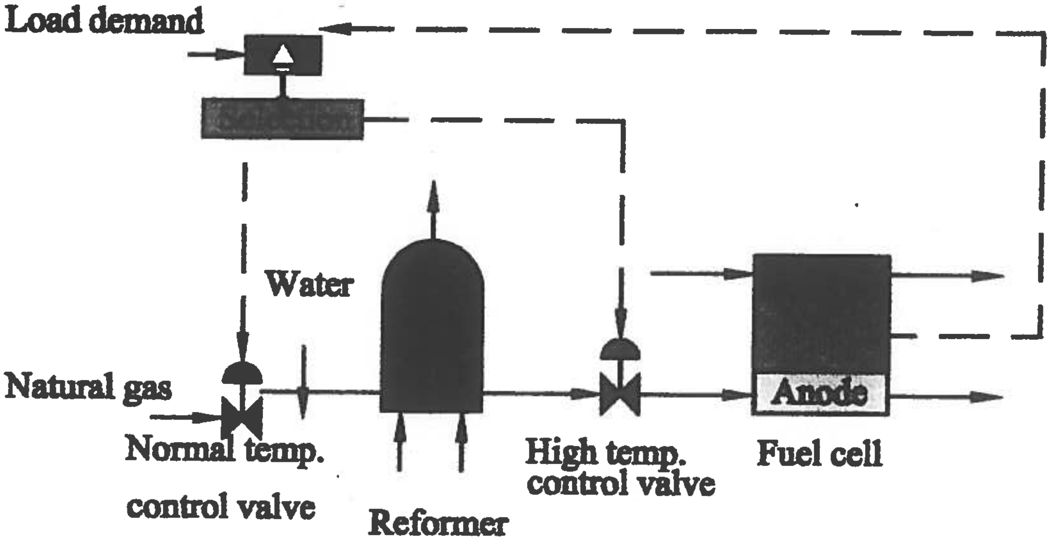


Fig. 7 Alternative fuel flow with normal or high temperature and the drawing of MCFC

Table (1): Characteristics for Selected Types of Fuel Cells

Types	Name	Cathode Material	Anode Material	Diaphragm	Electrolyte	Fuel	Oxidizing medium
First Type	Alkaline Fuel Cell	Activated Silver	Activated Nickel	Asbestos	25 - 35 % (KOH)	H_2	O_2
Second Type	Polymer Membrane	Membrane with Platen layer	Membrane with Nickel layer	Nafion Membrane	Catione Exxchanger Membrane, Nafion	H_2	O_2 or Air
Third Type	Phosphoric Acid Fuel Cell	Graphite with Platinum	Graphite with Platinum	Electrolyte in Plastic Matrix	H_3PO_4 in Plastic Matrix	H_2 form Natural Gas	O_2 from Air
Fourth Type	Carbonate Fuel Cell	Porous Nickel or Silver, Platen	Porous Nickel, Platen	Stable form matrix from Mg O , with Saturated lectrolyte	Melted Alkaline Carbonate in Porous Matrix	H_2 form Natural Gas and Gasified Carbon	O_2 from Air
Fifth Type	Hard Oxide Fuel Cell	Nickel in Zirconium Oxide (ZrO_2)	Platinum Spots	Cathode services as separator at the same time	ZrO_2 - Ceramic	H_2 and CO from Gasified Carbon	O_2 from Air

reliability for residential, commercial, and industrial customer by providing back up and ride-through during power outages.

The standard battery used in energy storage applications is Lead-acid battery. A Lead-acid battery reaction is reversible, allowing battery to be reused (rechargeable). These are also some advanced batteries e.g. Sodium/Sulfur, Zinc/Bromine, and Lithium/Air batteries that are nearing commercial readiness and offer promise for future utility applications.

3-6 Superconducting Magnetic Energy Storage (SMES)

A (**SMES**) system stores energy in magnetic filed created by the flow of direct current AC in a coil of superconducting material. To maintain the coil in its superconducting state, it is immersed in liquid Helium contained in a vacuum-insulated cryostat. **SMES** systems have a high cycle life and, as results, are suitable for application that require constant, fuel cycling and continuous mode of operation. Although, research is being conducted on large **SMES** systems in the range of 10 to 100 MW, recent focus has been on the smaller micro-**SMES** devices in the range of 1 to 10 MW. Micro-**SMES** devices are available commercially for power quality applications [13].

3-7 Supercapacitors

Supercapacitors are in the earliest stage of development as an energy storage technology for electric utility applications. An electrochemical capacitor has components related to both a battery and a capacitor. An electrochemical capacitor consists of two oppositely charged electrodes, a separator, electrolyte, and current collector. The energy is stored as a charge or concentration of electrons on the surface of the material.

Development of large-scale capacitors has been focused on electric vehicles, [14].

4- THERMAL ENERGY STORGE (TES)

TES can play an important role, as they provide great potential for facilitating energy saving and reducing environmental impact. **TES** systems have received increasing interest in recent years in terms of its applications, and the enormous potential it offer both for more effective use of thermal equipment. for economic, large scale energy substitutions. Indeed, **TES** appears to provide one of the most advantageous solutions for correcting the mismatch that often occurs between the power supply and demand of energy. **TES** deals with the storing of energy by heating, cooling, melting, solidifying or evaporating a material, the energy becoming available as heat when the process is reversed. **TES** may be classified into sensible heat storage and latent heat storage; the specific heat solidification/fusion or vaporization and the temperature at which the phase change occurs are obviously of controlling importance.

TES types depending on the storage duration;

- short-term storage (durinal storage) is used to face peak power loads of a few hours to a day long in order to reduce the sizing of the systems and or to take advantage of energy tariffs daily structure,
- middle or long-term storage (seasonal storage) is recommended when waste heat or seasonal energy loads can be transferred, with a delay of a few weeks to several months, to cover seasonal needs.

TES can be divided into low, moderate and high temperature **TES.** Low temperature **TES** being defined to mean the storage of <<heat>> enters and leaves the reservoir at below 120°C. Low temperature permits the storage of heat obtained from solar radiation from day to night or from summer to winter. It permits the storage of heat from central power plants, from hours of low to hours of high demand on both durinal and seasonal basis. The high temperature **TES** is higher than 450°C. The following features have to be taken into account when **TES** technology is designed:

- the storage media
- the temperature requirements
- thermal properties of storing media (ρ , C_p and K)
- energy sources
- the process with connection to the storage unit
- the storage container
- the cycling time (short-term or long-term)
- the charging/discharging time
- effect of the storage unit on the surrounding.

4-1 Sensible Heat Storage (SHS)

SHS is the most common process. It is easy to control and equipment is not very complicated. The storage unit is charged when the temperature of storage medium rises. The storage unit needs properly insulation properties, however, the thermal losses are expected to be small during the time between the charging and discharging processes. **Sensible heat** can be stored in packed beds, fluidized beds or in liquids. The storage medium may be solid, liquid or phase-change materials. Some of the storage materials that are suitable for thermal energy storage systems are given in Tables (2) and (3).

4-1-1 Packed bed thermal energy storage system

Packed beds as storage media are alternative, for they offer a compact structure due to relatively greater heat storage capacity as compared to system that utilize energy transporting fluid as the storage medium. New technologies may impose a limitation on the size and weight of the packed bed. These technologies depend on thermal properties of storage media,

Table (2): Some of the storage materials that are suitable for TES systems

Material	c J/kgK	ρ kg/m^3	k W/mK	Porosity Range of Bed, ε %
Water (at 60°c)	4179	983.3	0.654	0
Wrought Iron (0.5% c)	460	7848	59	40-0
Rock	880	2883	0.48	40-0
Porcelain	0.85	2420	0.36	-----
Glass	0.67	2500	0.21	------
Pebbles	0.88	1600	0.15	------

Table (3): Some of phase change storage materials

Material	Temperature, °c	Heat of fusion, kJ/kg
Ice.	0	80
C_{14} - C_{16} Paraffin.	2--7	152
Calcium chloride Hexahydrate ($cacl_2.6\ H_2O$).	29.7	170
Paraffin Wax (0.2% oil).	52--54	243--254
Ammonium Alum ($NH_3\ .\ AL(so)_{42}\ .\ 12\ H_2O$).	94	234

particles size, void fraction of these particles, shape and dimensions of the storage tanks and the kind of working fluid. Thermal behavior and performance of packed bed storage can be described by; temperature distribution inside the bed for working fluid and the storage medium as heat exchanger and the amount of thermal energy stored in the bed. The physical model of the cylindrical packed bed thermal energy storage is given in Fig. (8). The governing equations that describe the heat transfer process between the working fluid (air) and the storing medium (solid) in two dimensions and the numerical solution of the governing equations are presented as the following:

Air and Solid Equations:

Considering that the air flows axially, the conservation of mass yields:

$$\rho U = G = \text{constant} \qquad (4)$$

where G is air mass flow rate.

Neglecting the transverse heat transfer, the energy equation for air is:

$$\varepsilon \rho_a c_{p_a} \frac{\partial T_a}{\partial t} + G c_{p_a} \frac{\partial T_a}{\partial Z} = S_a \qquad (5)$$

where ε is the void fraction, which is the ratio of the air volume in the bed to the total bed volume, and equal to 0.3 in the present study. S_a represents the heat sink term during charging in the air equation and can be written as:

$$S_a = -h_v (T_a - T_s) \qquad (6)$$

where h_v is related to the air mass flow rate and the solid diameter, and calculated using the following formula;

$$h_v = 0.7(G/D_s)^{0.75} \qquad (7)$$

The momentum equation yields for low speed flow of air at constant pressure throughout the field. The conservation equation, which is applicable to the solid field, is the energy equation. The radial heat conduction in the solid is taken into consideration, in addition to the axial

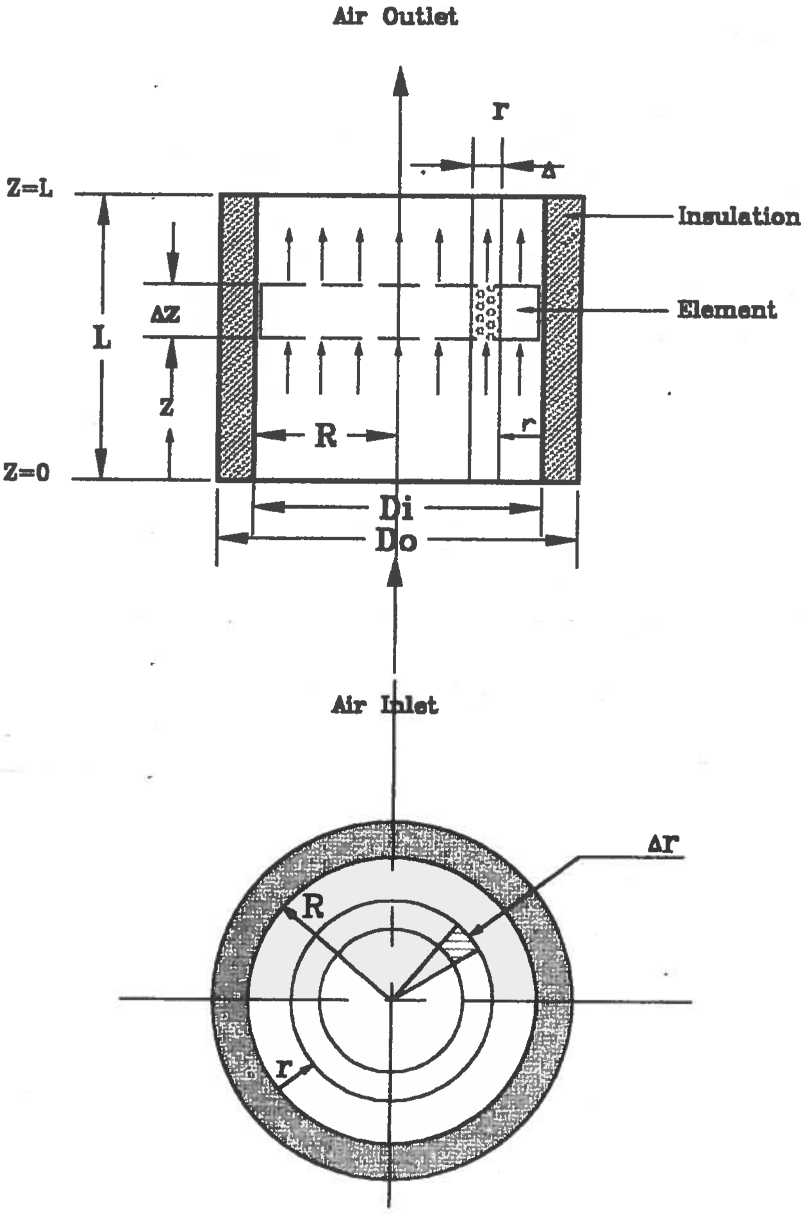


Fig.8 The Physical Model of cylindrical Packed Bed Storage

conduction. The transient temperature distribution of the solid phase is governed by the following energy equation in two-dimensions:

$$(1-\varepsilon)\rho_s c_{p_s} \frac{\partial T_s}{\partial t} = k \frac{\partial^2 T_s}{\partial Z^2} + k \left(\frac{\partial^2 T_s}{\partial r^2} + \frac{1}{r}\frac{\partial T_s}{\partial r} \right) + S_s \qquad (8)$$

where S_s is the heat source arising form the heat transferred from the air to the solid during charging and is expressed as:

$$S_s = h_v \ (T_a - T_s) \qquad (9)$$

-Initial and Boundary Conditions:

The initial and boundary conditions applicable to air energy equation are described as follows:

at t = 0 $T_a = T_h$ for Z = 0 for all r

$T_a = T_o$ for Z 0 for all r

where T_o is the ambient temperature.

at Z = 0 $T_a = T_h$ for all t and r

The initial condition applicable to the solid energy equation is written as:

at t = 0 $T_s = T_o$ for all r and Z

The boundary conditions for the solid along the radial direction are :

at r = 0 $T_s = T_w$ for all t and Z

at r = R = $B_D / 2$ $\frac{\partial T_s}{\partial r} = 0$ for all t and Z

The solid temperature satisfying the energy equation at both boundaries specifies the axial boundary conditions for the solid phase.

at Z = 0 for all t and r

$$(1-\varepsilon)\rho_s c_{p_s} \frac{\partial T_{s(0,r,t)}}{\partial t} = k \frac{\partial^2 T_{s(0,r,t)}}{\partial Z^2} + k \left[\frac{\partial^2 T_{s(0,r,t)}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{s(0,r,t)}}{\partial r} \right] + h_v \left[T_{a(0,r,t)} - T_{s(0,r,t)} \right] \qquad (10)$$

at Z = L for all t and r

$$(1-\varepsilon)\rho_s c_{p_s} \frac{\partial T_{s(L,r,t)}}{\partial t} = k\frac{\partial^2 T_{s(L,r,t)}}{\partial Z^2} + k\left[\frac{\partial^2 T_{s(L,r,t)}}{\partial r^2} + \frac{1}{r}\frac{\partial T_{s(L,r,t)}}{\partial r}\right] + h_v\left[T_{a(L,r,t)} - T_{s(L,r,t)}\right] \quad (11)$$

-Numerical Solution:

The above equations are spatial differential equations, and are solved along with their initial and boundary conditions simultaneously using a finite difference method and Thomas Algorithm [15]. The time and space derivatives in the air equation are discretizted using forward and backward differencing, respectively. Having solved the energy equation numerically, the energy stored in the bed can be numerically calculated using the obtained solid temperature field at time step k+1, by the following double integral.

$$E_s = 2\pi\,(1-\varepsilon)\rho_s c_{p_s}\left(\int_0^L \int_0^R (T_{si}-T_o)\, r\, dr dZ\right) \quad (12)$$

Study of improved performance of the plate heat exchanger with packed glass beads and mini-longitudinal chemicals on plate surface is presented by Wang et al. [16]. Figure (9-11) show the schematically diagrams of the experimental facility of their system which is composed of a heating fluid loop, a cold fluid loop and the test section. Water was taken as testing fluid, the water tank, pump and connecting tube make up to hot water loop. The regulator valves control the flow rate. The heater in the tank, which was regulated by applied electric voltage, maintains the temperature of water at the inlet of the experimental section. The water serves as the cool fluid, which directly drain away after passing through the test section. Their experiments were conducted to evaluate the pressure drop and heat transfer for the plate heat transfer element with packed glass beads and mini-longitudinal channels on plate surface. The improvement in reduced flow resistance and enhanced heat transfer was obtained with such combination (plate heat exchanger with packed glass beads).

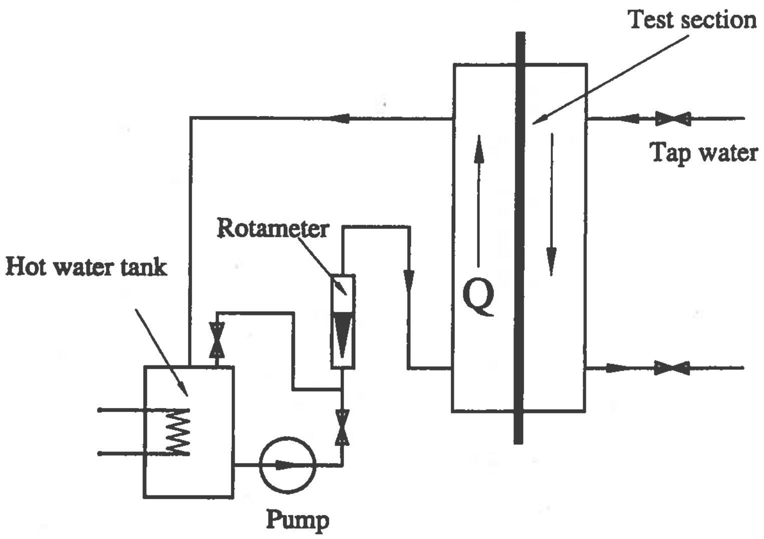


Fig.(9) Experimental System

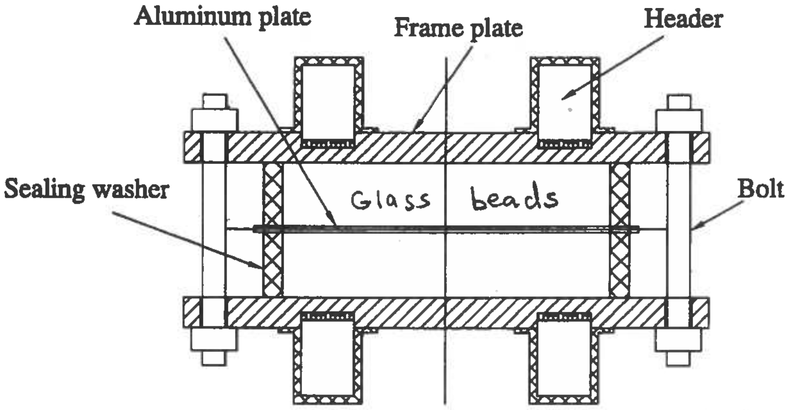


Fig.(10) Test section

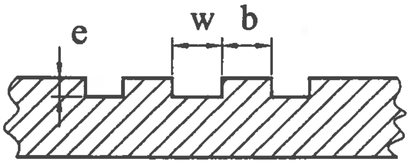


Fig.(11) The Geometry of the Longitudinal

4-1-2 Fluidized Beds Thermal energy storage:

The fluidized beds used as heat exchanger. The performance of the fluidized bed is proved to be entirely dependent on choice of solid materials (e.g. type and size), and choice of the fluid (gas or liquid). For example, thermal energy storage in fluidized beds of sand increases the efficiency by improving the heat transfer characteristics. Figure (12) shows the thermal energy storage in fluidized bed. The mathematical modeling of fluidized bed rice husk gasifier Part-11 model sensitivity was presented [17].

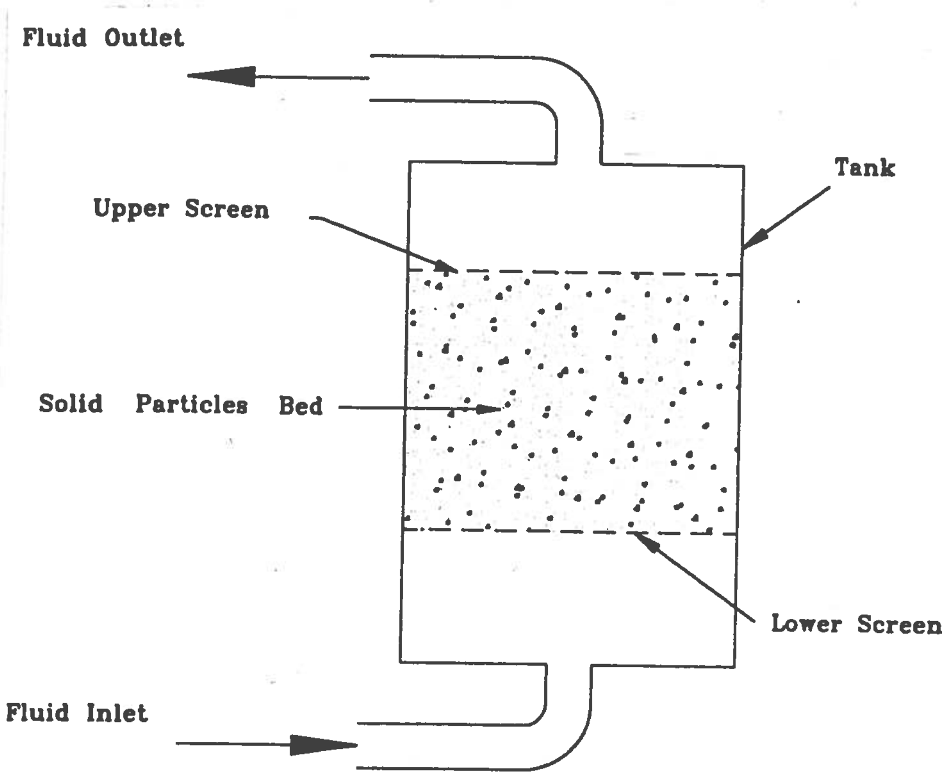


Fig. 12 Fluidized bed for thermal energy storage.

4-1-3 **Thermal energy storage in liquids:**

Water is a suitable thermal storage for the low-temperature range while organic oils and molten salts are suitable thermal storage for the high-temperature ranges. The fluid may be pressurized or unpressurized. Liquid storage store can be located above-ground or under-ground. The total energy that may be stored in liquids are limited by the size of the insulated tank and the percent of the energy needed by the load that is utilized. Aquifer is natural formation of the water-bearing rocks, sand or gravel found at nominal depths below the soil zones. They have physical properties of porosity and permeability, which make them capable of receiving storing and transmitting water.

4-2 Latent Heat Storage (Phase-change):

Among several thermal energy storage technologies, the latent heat thermal energy storage systems (**LHTES**) using phase change materials (PCMs) that are useful in charging and discharging a large amount of heat during melting and solidification. The **LHTES** systems are considered to be very promising to reduce CO_2 emissions and to mitigate global warming. The phase-change storage system is basically a heat exchanger in which a solid under goes a phase change due to heat. The storage of the thermal energy as latent heat occurs in an isothermal process. The absorption (charging) or extraction (discharging) of relatively large amount of thermal energy accompanies this process. On charging, the collector fluid, or an intermediate fluid, passes through the heat exchanger either inside pipes or by getting into direct contact with the solid. When the solid temperature rises to the melting temperature a phase change occurs. On discharging, the return cold fluid from the load or an intermediate fluid is switched to the heat exchanger in the storage bed.

The storage material reversibly changes to the original phase, while transferring energy to the fluid. Different phase change materials have been used for low-temperature applications. These materials include organic and inorganic compounds.

Andujar at al [18] presented thermal storage system evaluation. An evaluation follows of the solar thermal storage based on an eutectic mixture of phase change materials. Main parameters of the charge/discharge cycles (inlet/outlet temperatures, mass flows, and charge/discharge rates) were varied to simulate different solar multiples. The net thermal-to-thermal efficiency of their system was determined to be 72%, once the energy requirements to drive it were discounted. Thermal loss coefficients of both were measured and found to be 0.327 and 0.265 W/m^2 K for the hot and cold tank, respectively.

Energy calculation of latent heat energy storage system is conducted by Ahmet [19]. High temperature **LHTES** systems for solar ranking engines are presented by Takeo et al. [20]. Their paper describes the design of high-temperature **LHTES** tank including contact melting process in the vertical cylindrical capsule, and clarifies the charging characteristics. The schematic model for high-temperature **LHTES** accumulator is given in Fig. (13). They introduced an application of solar ranking engine, which is composed, of solar collector, thermal energy storage tank, and steam expander. Steam from this tank operates the steam expander. Figure (14) shows the outline of this solar ranking cycle system.

Thermal energy storage and heat transfer in phase change material inside the spherical capsules of packed bed thermal storage system are presented by Yingqui et al. [21]. A typical module, which consists of a hollow tube with a heat transfer fluid flowing through the PCM spherical capsules is shown in Fig, (15). **LHTES** in a capsule is of practical importance for peak cut of electricity demand in the summer season. Figure (16) shows

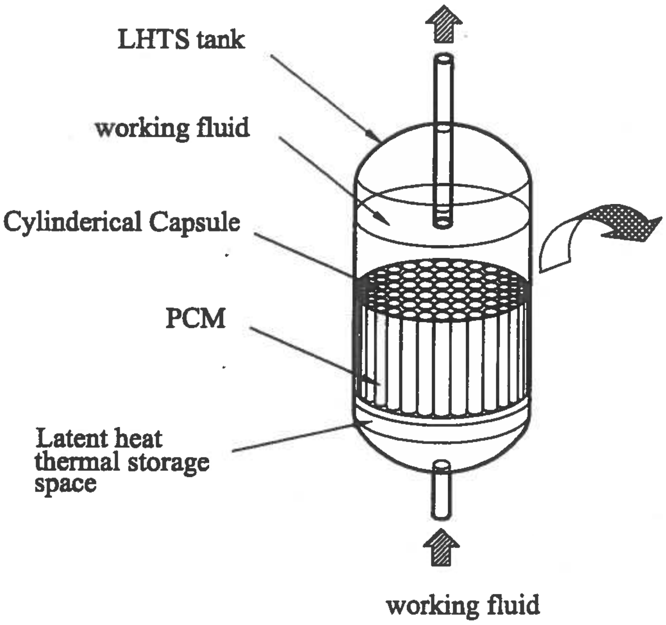


Fig.(13) Schematic model for
high-temperature LHTES accummulator

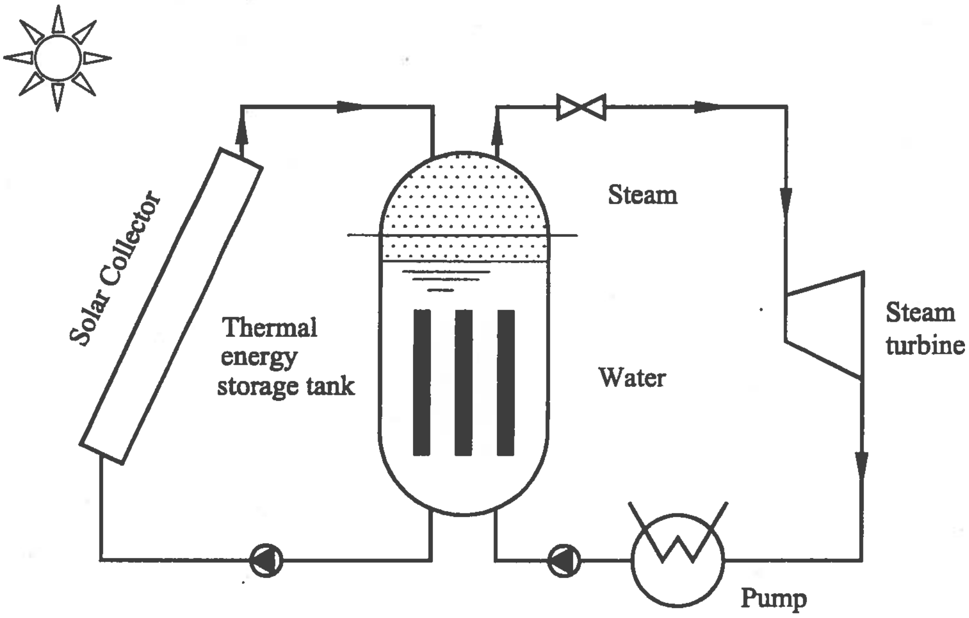
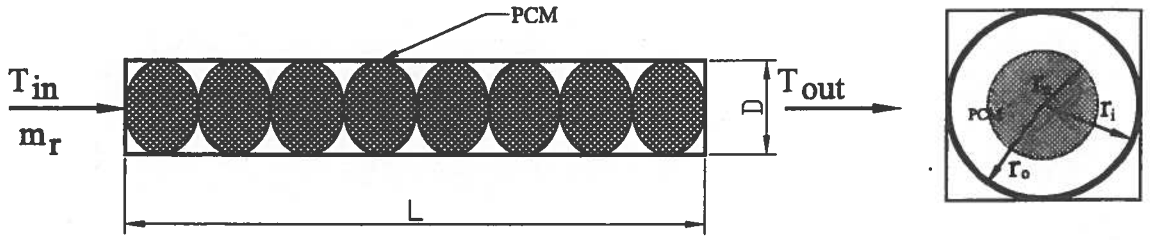


Fig.(14) Solar Rankine system



(a) cross section (b) longitudinal section

Fig.(15) The schematic of latent heat storage module

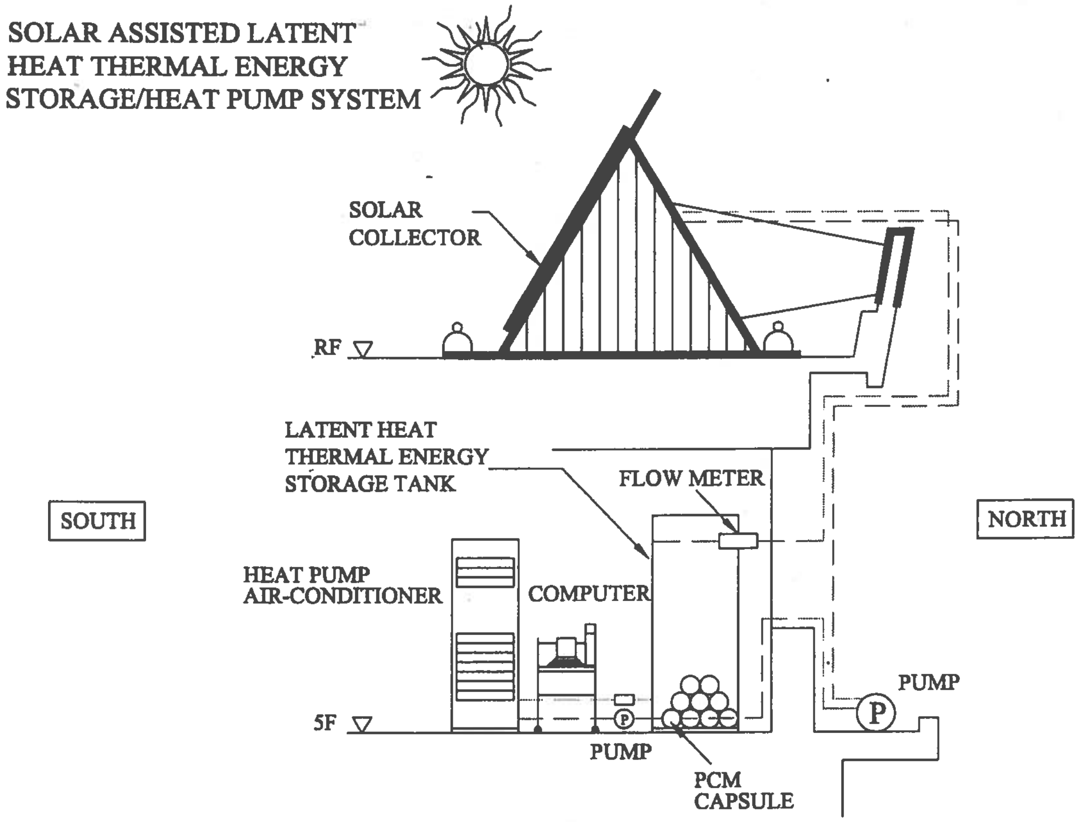


Fig.(16) Borehole seasonal energy storage system the seasonal energy storage system as an application for space heating/cooling system for the high-story building [22]. The system recovers the heat generated by the space cooling and refrigeration utilized in summer season. During the summer month, this excess heat is used for charging a heat store (bore-hole unit, and during the winter season, the heat extracted from bore-hole unit and solar thermal energy collected by the solar collector are used to heat the high buildings. Then, the winter cold energy is stored and utilized as cold energy source in summer.

5- RENEWABLE ENERGY STORAGE TECHNOLOGIES (RES)

Because the greatest amount of energy from some solar and renewable energy resources, such as sunlight and wind, is available only at certain times of the day, it is important to be able to store the energy captured from the resources for later use. **RES** system is essential component and plays a very basic role to provide the renewable energy applications with energy during the mismatch that often occurs between the power supply and demand load. Advanced energy storage technologies provide a kind of reservoir of power, and they extend our energy resources in ways many people might never have imagined fifty years ago. These technologies include advanced batteries, solar, wind, biomass, geothermal, Hydrogen, fuel cells and tidal & wave energy. Renewable energy is benign source and alternative energy.

5-1 Solar Energy Storage Technologies

Solar energy is the main source of the renewable energy. The primary solar energy technologies include photovoltaics, solar thermal electric and solar heating and cooling systems.

5-1-1 Photovoltaic (PV) technologies

PV systems are one of the fasted growing solar energy technologies. PV device, commonly called solar collector modules, use semiconductor material to directly convert sunlight into electricity. PV system consists of; modules + controller + solar batteries (for storing DC electricity generated by solar cell) + inverter (to converts DC electricity into AC). The solar cells are used to power remote residence, satellites, highway signs, water pumps, communication stations, navigation buoys, street light, billboard, and calculators. PV system is capable to provide energy during a utility outage. Figure (17) shows the block diagram of typical PV system with energy storage system for power of commercial building which is combined with the main grid, [23]. Home and camping solar systems were designed to offer a wide range of electrical power solutions in order to supply remote home and camping sites with its electrical needs. Today, you can live away from the grid, or go camping and have your own solar generator with you to supply electricity whenever you want. Some of PV systems (home PV solar system, street lighting and billboard systems) as examples were applied in different sites in Egypt as shown in Figs. (18-20), [24].

5-1-2 Solar thermal energy storage (STES)

STES systems use solar collectors to absorb and convert the sunlight into heat. The heat can be used for heating and cooling homes and buildings, water heating, air conditioning, salt production, drying, and water desalination. A study on optimal condition of regenerating performance in a solar absorption cooling system as an application is presented by Kwang et al. [25]. As shown in Fig. (21), their air-conditioning system composed of four components; a regenerator, a heat exchanger, a dryness storage

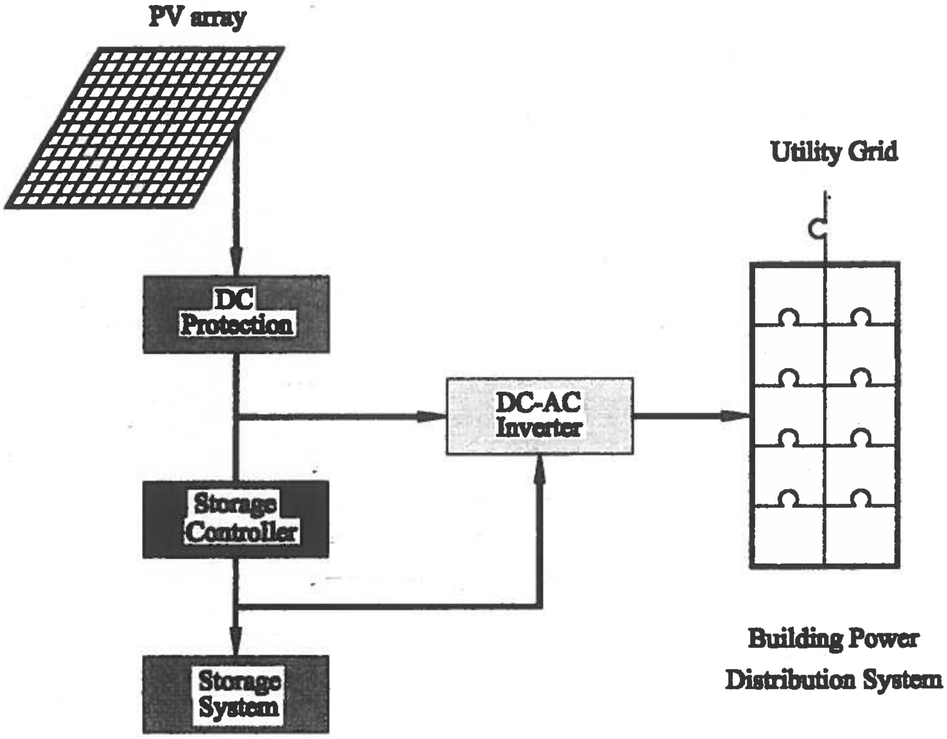


Fig.(17) Block diagram of a typical PV system with energy storage system.

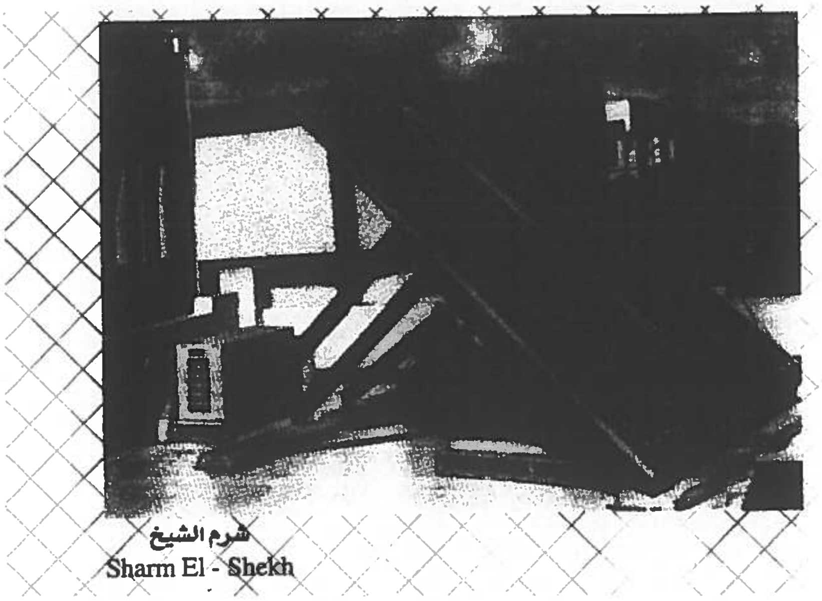


Fig. (18): Photograph of remote home completely depends on PV system.

Fig. (19): Photograph of marine street lighting system.

Fig. (20): Photograph of billboard system.

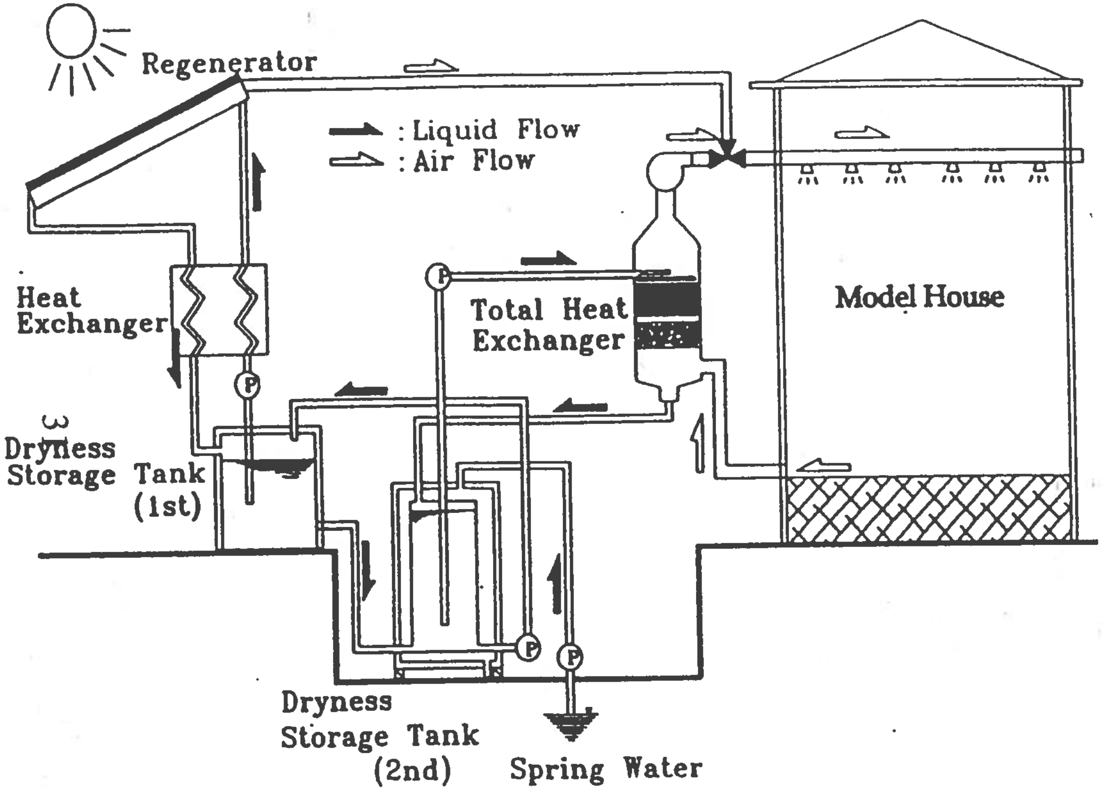


Fig. 21 Schematic of suggested solar conditioning system

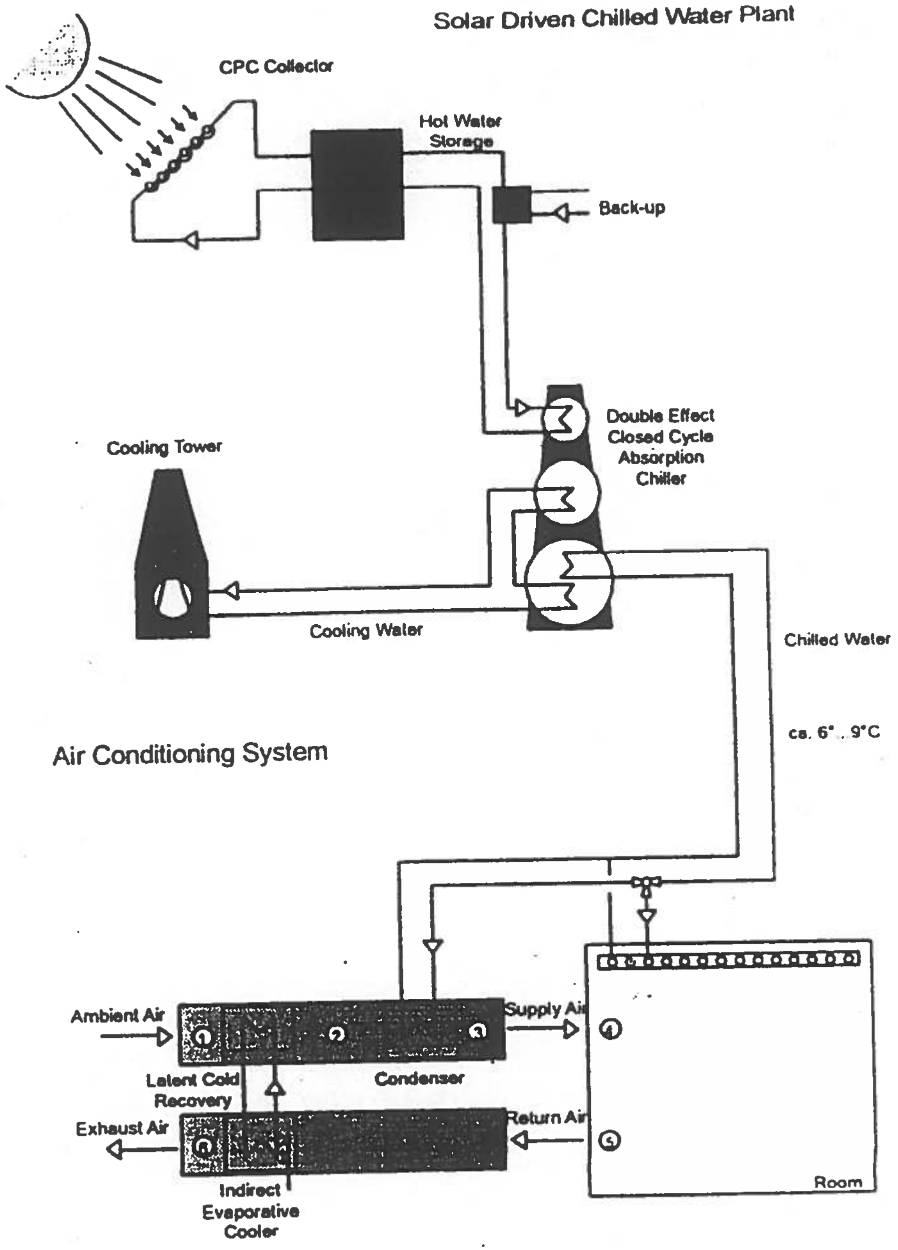


Fig. 22 Schematic of innovative system for solar air-conditioning

tank, and a sensible heat exchanger. This system allows house to keep air-conditioning, cooling in summer and heating in winter through year. Innovative system solar air-conditioning is studied by Wolfgang Kessling [26]. A schematic diagram of the solar air-conditions system is shown in Fig. (22).

A typical seasonal system design of central solar heating plant with seasonal storage unit is shown in Fig. (23), [27].

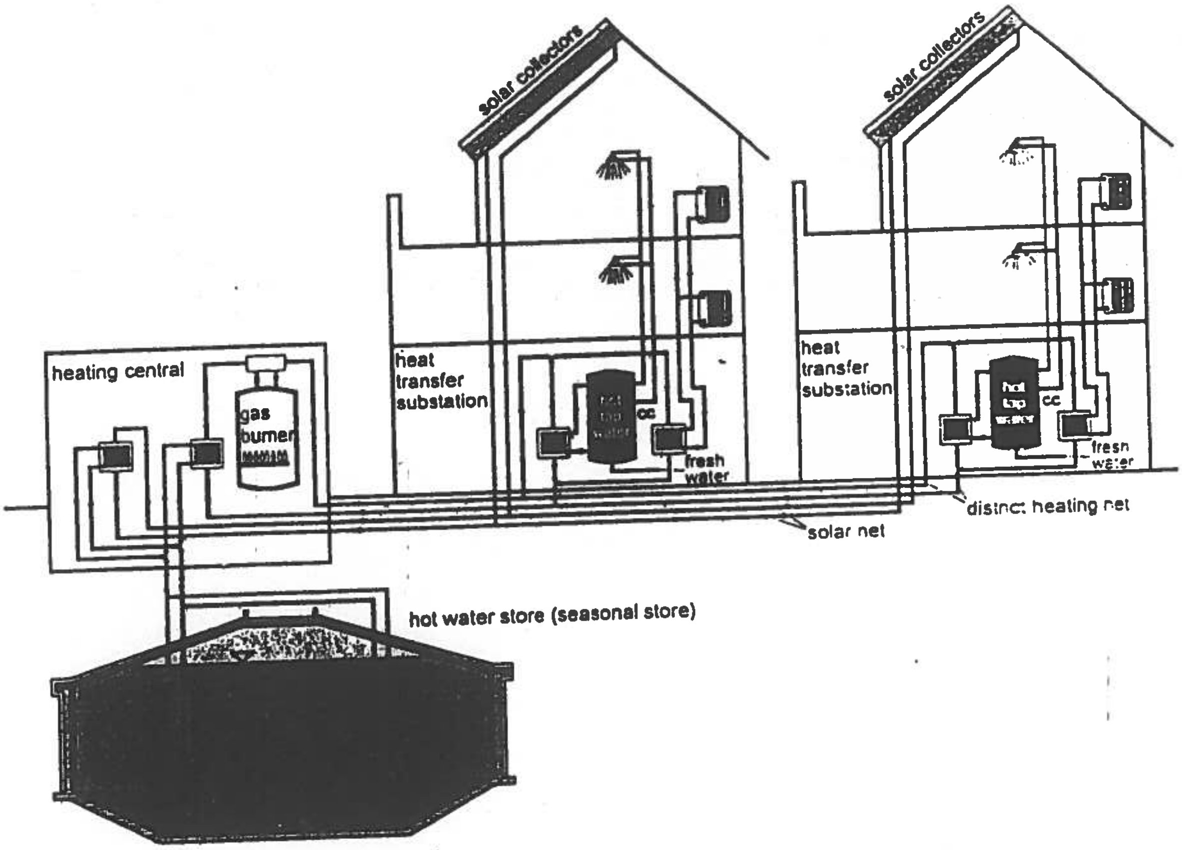


Fig. 23 A seasonal system design of the air-condition~~s~~ing system.

There are many projects of solar industrial process heat and waste heat recovery is applied in Egypt. Its main objectives are to demonstrate and field test solar industrial process heat and waste recovery system in food industrial. Two projects were implemented through the program of Ministry of Electricity and New and Renewable energy Authority (NREA). Figure (24) shows flow diagram of the poultry processing plant project (design, construction, operation, training, and testing of the system). The project saves about 345ton equivalent oil/year and the project started in May 1990. Another project is Misr Helwan Spinning and weaving (Textile). The flow diagram of another project is shown in Fig.(25). The project saves about 565ton equivalent oil/year and the project started in February 1990. Utilization of solar energy and waste heat is presented by Kamil [28]. A heat pump and thermal energy storage unit was combined in an experimental set-up as shown in Fig. (26) to utilize solar energy and waste heat efficiency at low temperature range (10-50°C). The Calcium Chloride Hexahydrate was used as the thermal energy storage medium and water was used as the working fluid between the storage tank and the collectors.

5-2 Wind Energy Storage Technologies

Wind energy is widely recognized as the most efficient and cost effective form of new renewable energy available in the world. Wind energy is an intermittent source of power. So, what do we do for power when the output of wind turbine is not sufficient to meet the demand for energy? Wind hybrid technology options mix with other power source and storage device to help solve this problem.

5-2-1 How wind turbines work?

Wind turbines use a rotor (blades), a power shaft, and a generator to convert the wind's kinetic energy into electrical energy. When wind passes over the rotor, it creates aerodynamic lift that causes the rotor to spin. This

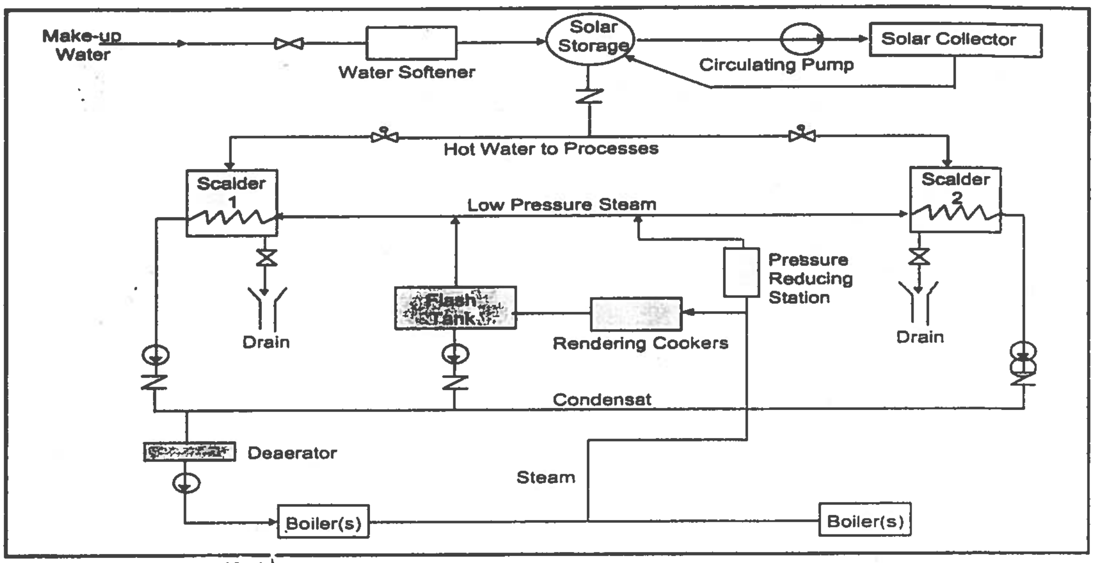


Fig. (24) General Poultry Energy System Flow Diagram

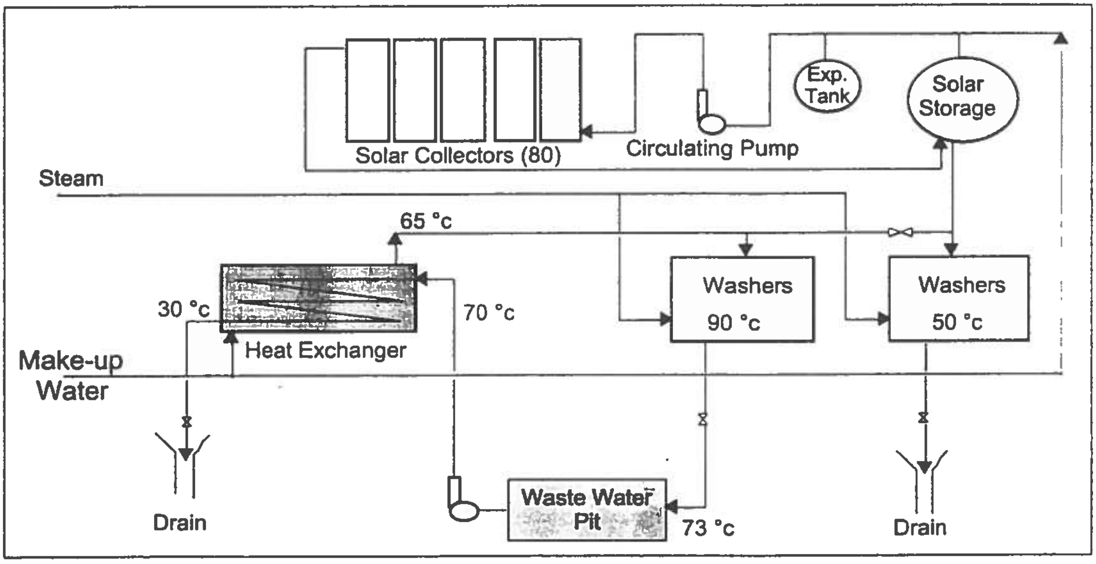


Fig.(25) Misr Helwan Spinning & Weaving Flow Diagram

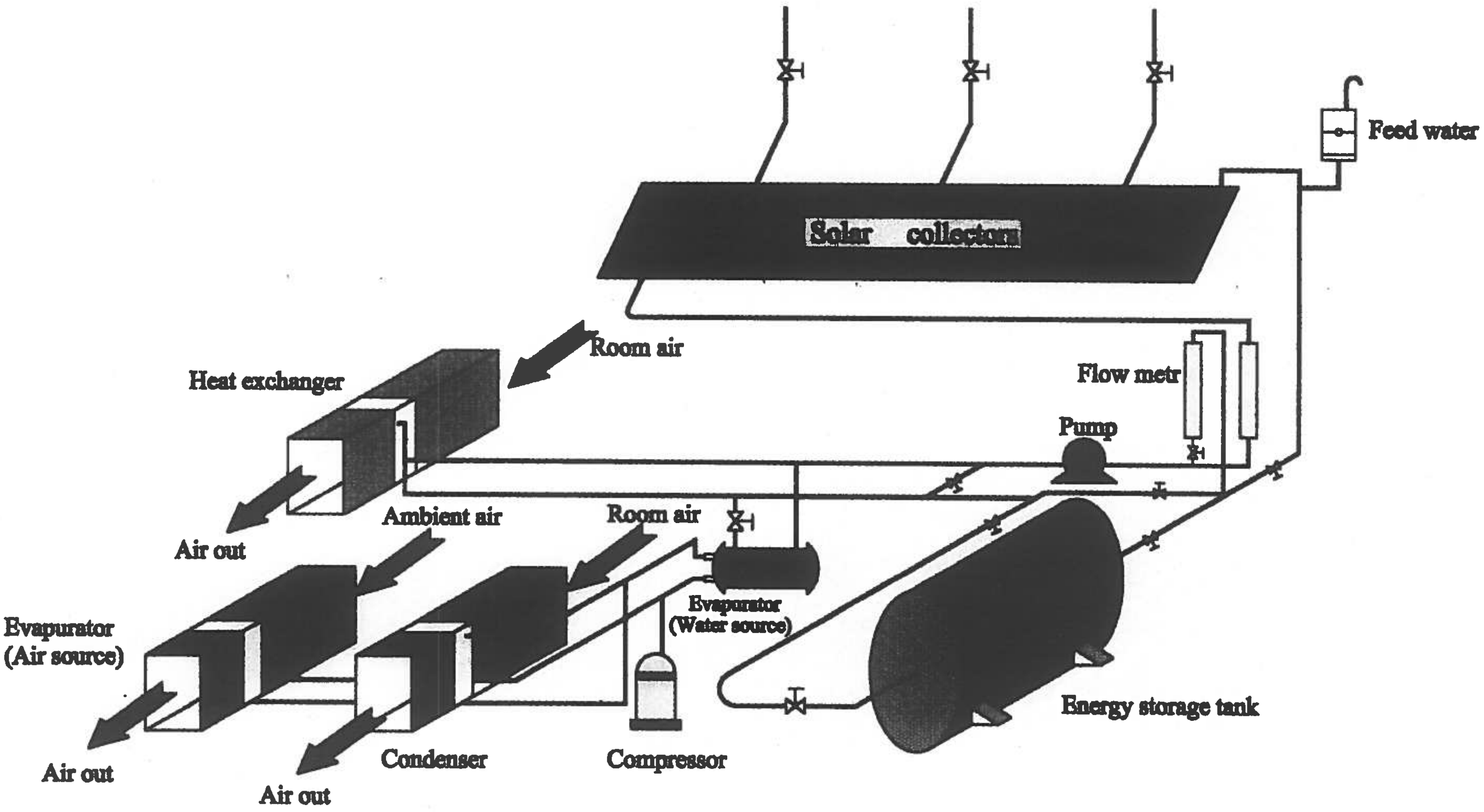


Fig. 26 Schamatic overview of the solar-assisted heat-pump system

rotary motion is used to drive the generator and produce electricity. Wind turbines are also, equipped with a rotor control to adjust spin rate and stop the motion of the blades. Because wind speed increases with height, wind turbines are mounted on towers. The amount of energy that a wind turbine produces depends on wind speed and the diameter of the rotor.

5-2-2 Types of wind turbines

There are two basic wind turbine systems; horizontal-axis wind turbine which, the rotating axis is parallel to the wind stream's direction of flow and the ground, and vertical-axis systems which, the rotating axis is perpendicular to the wind stream and the ground and can capture wind coming from any direction.

5-2-3 Wind turbines technologies

There are several hybrid systems as applications that considered to store and utilize the output power of the wind turbine.

The following applications as for examples will be illustrated, [29]. An integrated wind-batteries storage system is shown in Fig. (27).

A schematic diagram of hybrid wind-pumped hydro energy storage system is illustrated in Fig. (28), that utilized excess power from wind turbines to pump water to an upper reservoir, which can later be discharged when there is a lack of wind resources or an increased peak-load.

Figure (29) shows illustration of the hybrid wind-compressed air energy storage system. During periods of electric demand, the compressed air would expanded through an air turbine (as opposed to combustion turbine) that drives an electric generator. During periods of low electric demand and high wind speeds, the compressed air would be diverted to a

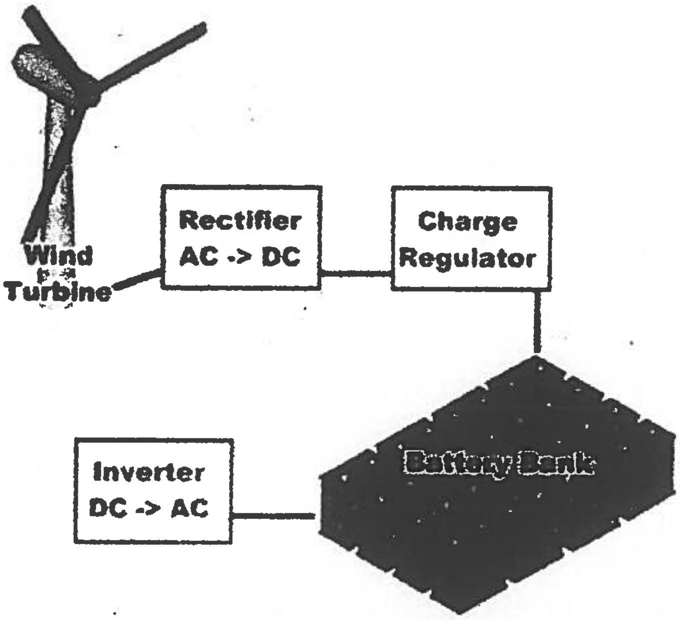


Fig. 27 Drawing of an integrating wind-batteries storage system

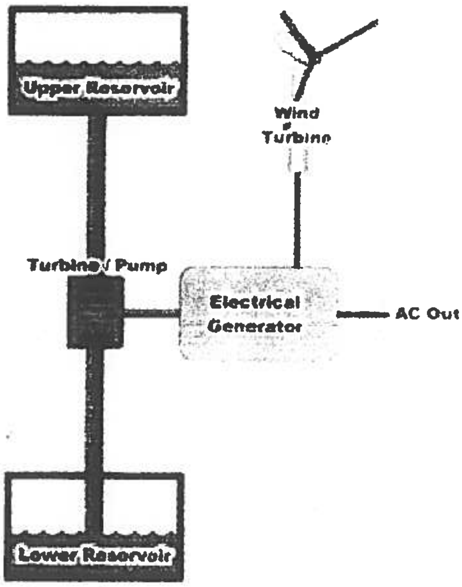


Fig. 28 Drawing of hybrid wind-pumped hydro energy storage system.

storage chamber. When the wind is intermittent, this compressed air would expand through the air turbine to reduce electric power.

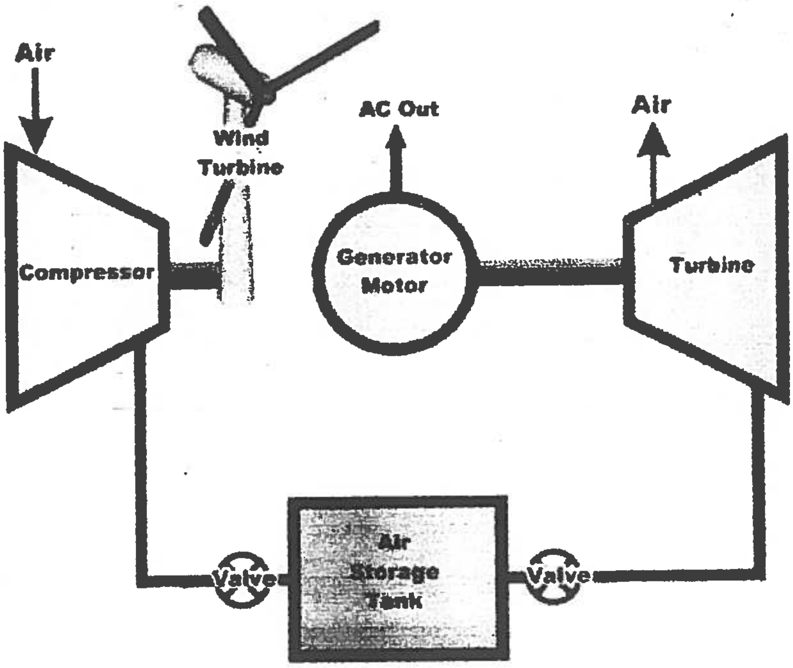


Fig. 29 Illustration of hybrid wind-compressed air energy storage system

5-3 Biomass Energy Storage Technologies

Biomass energy-the energy contained in plants and organic matter-is one of humanity's earliest sources of energy. Biomass resources include wood, wood waste, agricultural crops and their waste by products, solid waste, animal waste, waste from food processing, and aquatic plants and algae. Today's power plants burn biomass to generate electricity in a process knows as direct combustion (biomass is burned to produce steam, the steam turns a turbine and the turbine drives a generator, producing electricity).

Gasification - gasifiers are used to convert bimass into a combustible gas (biogas which used to drive a gas turbine). Biogas is distinguished from producer gas in where it is made through anaerobic digester (oxygen - free) that digestion of organic waste to generate gaseous fuel by bacteria. The process occurs in stages to successively break the organic matter into simpler organic components. The product is a mixture of methane (CH_4), carbon dioxide (CO_2), and some of other gases (O_2). Most digestion systems produce biogas is between 55% and 75% methane by volume, [30]. Biogas once treated to remove sulfur compounds, can be used in many applications, including stationary power generation. Biogas is a suitable fuel for engine generator sets, small gas turbines, and some kind of fuel cell. Figure (30) shows a schematic of hybrid wind-anaerobic digester as new technology of energy storage system.

Biofuels are made from biomass resources such as grasses, trees, trash, and waste from the forestry industries. Biofuels include ethanol, methanol, biodiesel and additives for reformulated gasoline. Biofuels are considered clean domestically fuels.

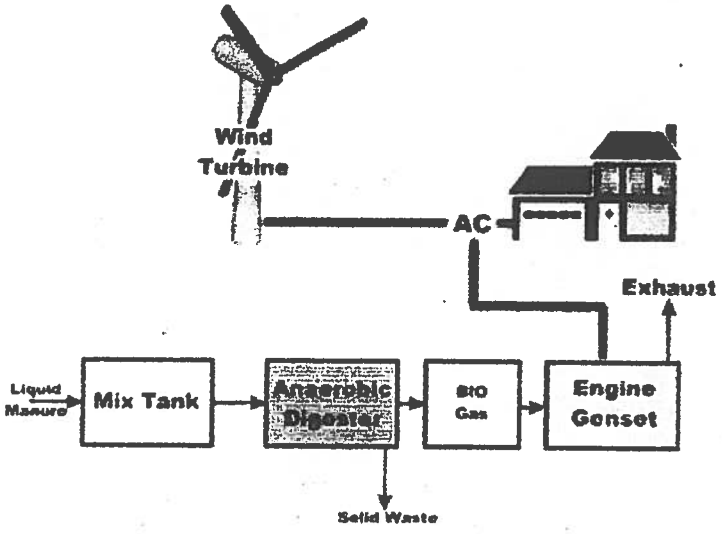


Fig. 30 Schematic diagram of hybrid wind-anaerobic digester system

5-4 Geothermal Energy Storage Technologies

Miles beneath the earth's surface lies one of the world's largest energy resources-geothermal energy. Today, the geothermal energy enormous energy reservoirs are used for cooling and heating, etc. Geothermal energy is the heat contained below the earth's crust. This heat is brought to the surface as steam or hot water-created when flows through heated permeable rock - and used directly for space heating in homes or converting into electricity. Geothermal is stored in hydro-thermal reservoirs, which are large pools of steam or hot water trapped in porous rock. To generate electricity, the steam or hot water is pumped to earth's surface where it drives a turbine that spin an electric generator.

5-5 Hydrogen Storage Technologies

Hydrogen made from renewable energy resources is a virtually inexhaustible, environmentally benign energy source that could meet most of our future energy needs. It's more versatile and has different uses. These uses include providing energy for factories, electric utilities, homes, vehicles and airplanes. Hydrogen also, a domestically help reduce our reliance on petroleum oil. Today, hydrogen is used primary in ammonia manufacturing, petroleum refining and synthesis of methanol.

Hydrogen is currently more expensive than traditional energy sources. Hydrogen is currently stored as a compressed gas or a cryogenic liquid in physical storage systems. Advanced hydrogen storage researches are currently to develop a solid - state storage system that is suffer than physical storage systems, and could potentially store more hydrogen per unit volume. Solid - state systems chemically or physically bind hydrogen to a solid - state material. In these researches, solid - storage system uses microscopic carbon tubes (carbon nanotubes) to adsorb hydrogen. This technology can store large volume of hydrogen at higher temperatures and at near ambient pressure levels.

The first widespread use of hydrogen as an energy source is likely to be in the transportation sector, where it will help reduce pollution. Internal combustion engines can be fueled with pure hydrogen, or hydrogen blended with natural gas. Vehicles can also be powered with hydrogen fuel cells, which are three times more efficient than a gasoline - powered engine. Hydrogen and oxygen are important components of advanced fuel cell technologies. Figures (31) and (32), [31] show the drawing of an alkaline fuel cell and phosphoric acid & Proton Exchange Membrane (PEM) fuel cell, respectively as two examples of fuel cells that using hydrogen gas. Fuel cells can also supply heat and electricity for homes and buildings.

5-6 Tidal and Wave (Ocean) Energy Storage Technologies

To produce power from tides, the motion of these tides, waves or currents is used to drive a turbine - generator.

Tidal power plants use the rising and falling sea tides to generate electricity. The plants use dam - like structure to trap water at high tide and release it at low tide. The water flow drives turbines that propel electricity-producing by generators. Tidal power plants require at least a 16-foot tidal range (difference between high and low tide). The simplest generates system for tidal plants, known as a barrage across an estuary. Sluice gates on the barrage allow the tidal basin to fill on the incoming high tides and to exit through the turbine system on the outgoing tide (known as the ebb - tide). Figure (33) shows drawing of Ebb generating system with turbine. Several different turbines are used in tidal power stations, for example, bulb turbine as shown in Fig. (34), [32].

Wave energy generation devices classified into; fixed and floating (oscillating water column) devices. Fixed generating devices are mounted either to the seabed or shore. The most common technique for harnessing wave energy is to use windmill - like turbines that generate electricity when water flows through them. Figure (35) shows schematic of an oscillating water column to generate wave energy, [33].

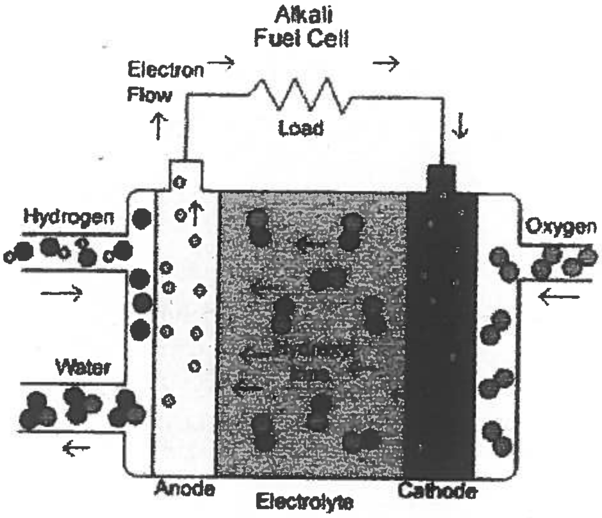


Fig. 31 Drawing of an Alkaline fuel cell

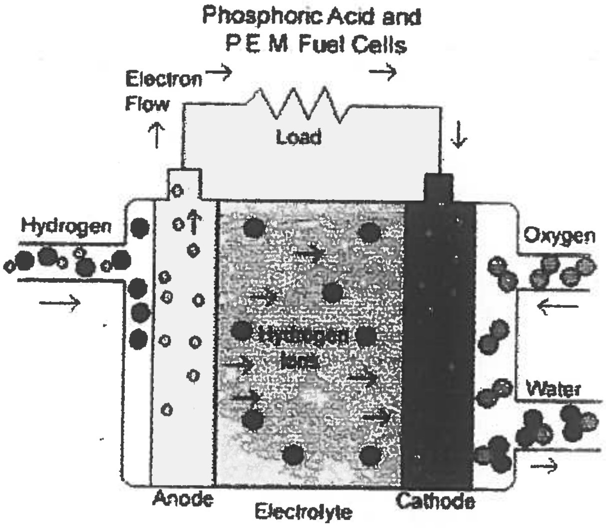
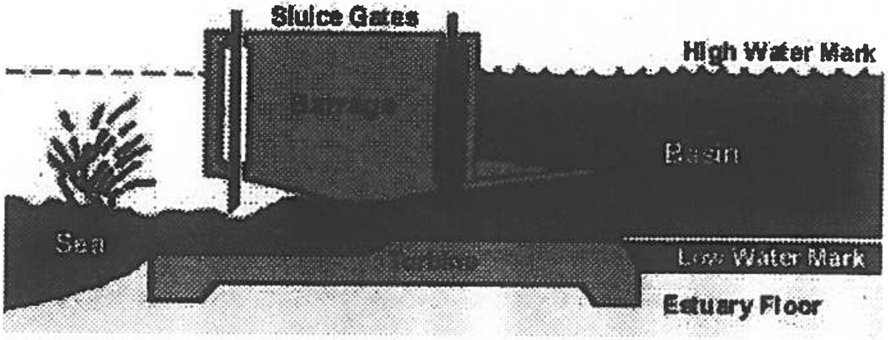
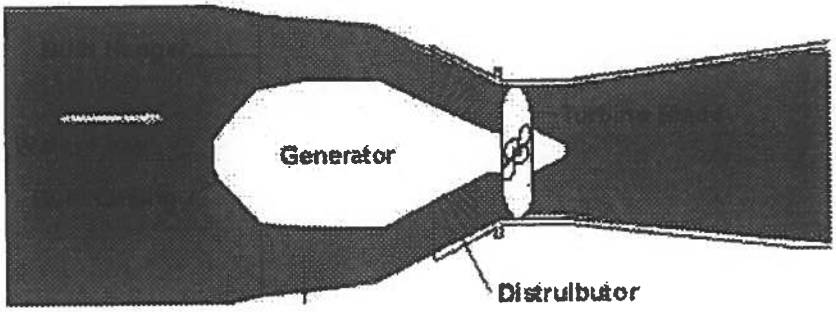


Fig. 32 Drawing of Phosphoric acid and Proton Exchange Membrane



Ebb generating system with a bulb turbine
(Adapted from Energy Authority of NSW Tidal Power Fact Sheet)

Fig. 33 Drawing of Ebb generating system with turbine

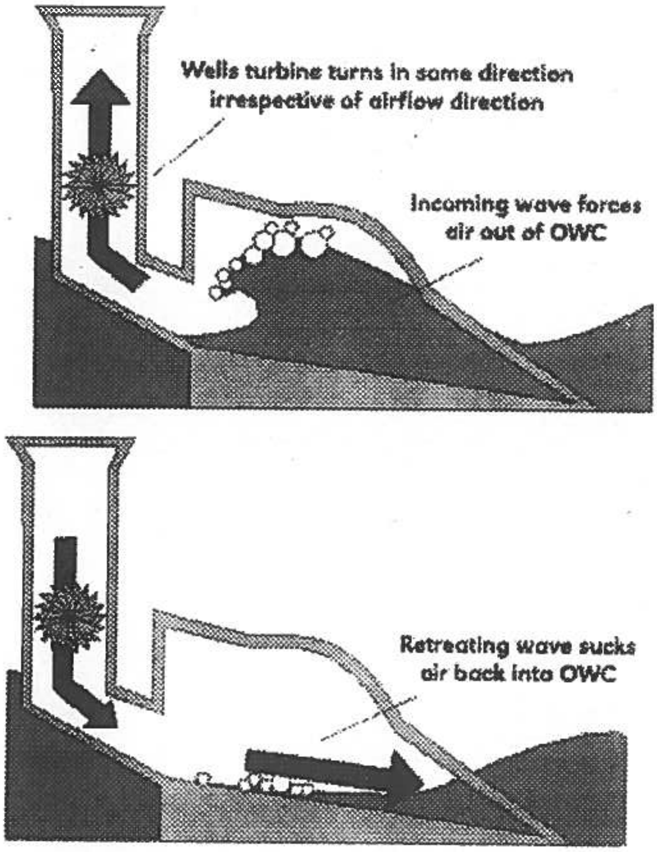


http://www.acre.murdoch.edu.au/ago/ocean/tidal.html 04 23/2002

Fig. 34 Drawing of bulb turbine

Tidal and wave energy technologies use a free and unlimited fuel; have minimum environmental impact, and provide a stable and domestic energy resources.

Tidal and wave energy systems also, produce nutrient - rich, desalination and agricultural water.



Schematic of an Oscillating Water Column
(Image courtesy of Fujita Research)

Fig. 35 A schematic diagram of an oscillating water column to generate wave energy.

6-CONCLUSIONS and RECOMMENDATIONS

This review article is focused on energy storage technologies as the following:

1- Recent technologies are used to improve the performance, increase the efficiency, reduce the costs of the energy storage energy systems.

2- In the world, utilities generate electricity from coal, oil and natural gas at low costs. While the gap is closing, renewable energy source are not yet cost-effective for large-scale electricity generation.

3- The most appropriate storage systems for such applications presently appear to be batteries. Advanced batteries have been stand-alone PV and wind systems for more than two decades throughout the world.

4- The ideal alternative conventional batteries must be cost-effective, compact, low maintenance and have a long installed life.

5- Hybrid systems that including energy storage systems are new technologies such as; wind-batteries hybrid system, wind-hydropower hybrid system and wind-anaerobic digester hybrid system, here, the costs can be substantially reduced by these technologies.

6- Solar energy storage technologies can be used for domestic water heater, space heating & cooling, drying, desalination, power generation and industrial processes.

7- High technology materials, aerodynamic blades, energy storage systems and advanced designs enable wind energy systems to compete with conventional energy sources for electricity production and water pumping where adequate wind resources exit.

8- Other technologies such as geothermal, tidal & wave energy, fuel cells and advanced storage technologies still need research and development to reduce the system' costs.

9- Anaerobic digestion, gasification technologies have been used world wide to produce gaseous fuels, electricity and fertilizer.

10- Researches continue to develop technologies that will make renewable energy storage systems (solar, wind, tidal, PV, etc.), particularly power generation-cost competitive with traditional sources (fossil fuels).

7- LIST OF SYMBOLES

A	Cross section area of the bed, m^2
B_D	Diameter of the packed bed, m
C_{Pa}	Specific heat at constant pressure for air, kJ/kgK
C_{Ps}	Specific heat at constant pressure for solid, kJ/kgK
D_i	Inner diameter of storage tank, m
D_o	Outer diameter of storage tank, m
D_s	Diameter of solid balls, m
E_s	Energy stored in packed bed, kJ
G	Mass flow rate of air per unit area, kg/m^2s
h_v	Volumetric heat transfer coefficent, kJ/m^3sK
i	Axial space index value from 1 to MZ
j	Radial space index from 1 to MR
K	Time index value from 1 to N
k	Thermal conductivity , kJ/mks
L	Length of the packed bed, m
r	Radial coordinate
R	Radius of packed bed, m
R_i	Inner radius, m
R_o	Outer radius, m
S	Heat source or sink, kJ/m3s
T	Temperature, °C
t	Time, s
U	Velocity, m/s
X	Horizontal direction
Z	Axial direction

Greek Letters :

ε	Void fraction
ρ_s	Density, kg/m^3

Subscripts :

a	Air
D	Diameter
h	Hot
m	Medium
o	Ambient condition
s	Solid

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