Solar Biogas Digester with Built-In Reverse Absorber Heater

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ABSTRACT

In this work the design, fabrication and investigation of a solar biogas digester with built-in RAH (Reverse Absorber Heater) is presented. The maximum temperature (50°C) inside of the methane tank was taken as a main parameter at the design of the digester. Using energy balance equation for the case of a static mass of fluid being heated; the parameters of thermal insulation of the methane tank were counted. The biogas digester is consisting of methane tank with built-in solar RAH to utilize solar energy for the heating of the slurry prepared from the different organic wastes (dung, sewage, food wastes etc). The methane tank was filled up to 70% of volume by organic wastes of the GIK Institute sewage, firstly, and secondly, by sewage and cow dung as well. During three months (October-December, 2009) and two months (February-March, 2010) the digester was investigated. The solar irradiance incident to the absorber, slurry's temperature and ambient temperature were measured. It was found that using sewage only and sewage with cow dung the retention times was 4 weeks and two weeks respectively and biogas quantity produced was 0.4 and 8.0 m^3 respectively. In addition, biogas upgradation scheme for removal of carbon dioxide, hydrogen sulphide and water vapor from biogas and conversion of biogas energy conversion into electric power is also discussed.

Key Words: **Solar Biogas, Digester, Methane Tank, Reverse Absorber, Built-in Heater, Solar Energy.**

1. INTRODUCTION

It is known that consuming energy is proportional to the quality or standard of life. There is a close relationship between energy consumption and the GNP (Gross National Product). It is obvious that for further development of the country additional sources of energy is required, which are cheap, safe and environmentally compatible with respect to the action on possible wastes. Utilization of renewable energy is one route to help in solving the above mentioned problems. In particular, biogas as a source of renewable energy is produced by biotechnology and used wide on residential scale [1-9]. The biogas was produced for the very first time in 1814 by Davy from organic wastes. In 1900 production of biogas was started in Bombay, India. Biogas consists of 55-70% CH_4 (Methane) and around of 27-44% CO_2 (Carbon Dioxide) and less than 1% H_2 and H_2S. At present biogas is used widely in some countries for lighting, machines, and vehicles, generators, cooking and heating. Biogas generation is suitable for small to large scale operation and at present is realized in a number of developed and developing countries including USA, Hungary, China, India etc. Since 1990s biogas projects construction in China has developed steadily by the end

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of 1998, there were altogether 6.88 million household biogas digesters [1]. In Russia biogas digesters are used for processing of hard dung into biogas. Over the last few years the very first biogas digesters were constructed in Tajikistan as well [2,5] and it was found that the digesters can work with sufficiently high efficiency in mountain areas as well.

The biogas yield rate increases about two times if the temperature increases up to 5^{o}C. In colder climates the process of digestion goes at heating up to 35^{o}C. For heating of biomaterial solar energy is used in some digesters of laboratory (a bottle-type where a bioreactor has small volume) [2] or industrial type [5]. There are two methods of the heating of digester by solar energy i.e. passive and active [4]. In the case of passive heating, for example, the digester's body can absorb the solar energy as a receiver through a lid or dome. If an active method is used the digesters consist of two basic parts: solar collector and bioreactor (methane tank) connected through pipes, heat exchanger and pump. In the whole, this system is more complicated and expensive. The laboratory type biogas digester with built-in solar collector and air heat exchanger, where natural convection was realized, had some advantages as compared to the conventional digester due to the shorter retention time (on 15%) and larger amount of produced biogas (in 20%) [8]. A reverse absorber heater is a new type of solar air collector where the convective and radiative heat losses are reduced. In this paper, design and fabrication of a biogas digester with built-in solar RAH making the system cheaper, more compact and reliable in the operation is presented and discussed in detail.

2. DESIGN AND FABRICATION OF THE BIOGAS DIGESTER

The biogas digester consists of a methane tank with built-in solar RAH to utilize solar energy for the heating of the slurry prepared from the different organic wastes as dung, sewage, food wastes etc. and is shown in from two sides in Fig. 1(a-b). The digester is a laboratory (or domestic) type and consists of vertical axes cylindrical plastic methane tank of size 0.98m in diameter; 1.05m in height and 0.8 m^3 in volume with a solar RAH installed under the methane tank. The methane tank is installed on a pyramidal support. Outer surface of the methane tank was covered by thermo insulated material and aluminum foil. The metallic absorber's surface was blackened and made rough, firstly to increase absorption of solar irradiation from outside and secondly to increase area of the surface from the inside accordingly to the increase in the heat transfer from absorber to slurry. The absorber's area is 80% of the methane tank's bottom area. The absorber's shape was made as circle. The inlet and outlet serve to load methane tank by slurry and release by tap respectively.

The solar RAH (Fig.1(a)) consists of horizontal axes cylindrical reflecting mirror and horizontal glass cover. Between horizontal glass cover and absorber there is air gap of 20mm. A horizontal absorber is a common element of the methane tank and solar reverse heater. The cylindrical reflector was used with radius of 0.9m and glazing size of 0.9x0.7m^2. The angle between the inclined glass cover and horizontal plane was 45^o, which is equal to the sum of latitude of location (34^o) and half of solar declination angle (11^o). The reflecting mirror as shown in Fig. 2 consists of the plane mirror (aluminum foil) strips pasted on plastic sheet. The size of every mirror strip was 0.1x1m. The sides of the cylinder have the same structure as the reflecting mirror: plane mirror, plastic sheet and plane metallic sheet. Fig. 3 shows fabricated solar biogas digester with flexible gas-holder.

3. EXPERIMENTAL SETUP

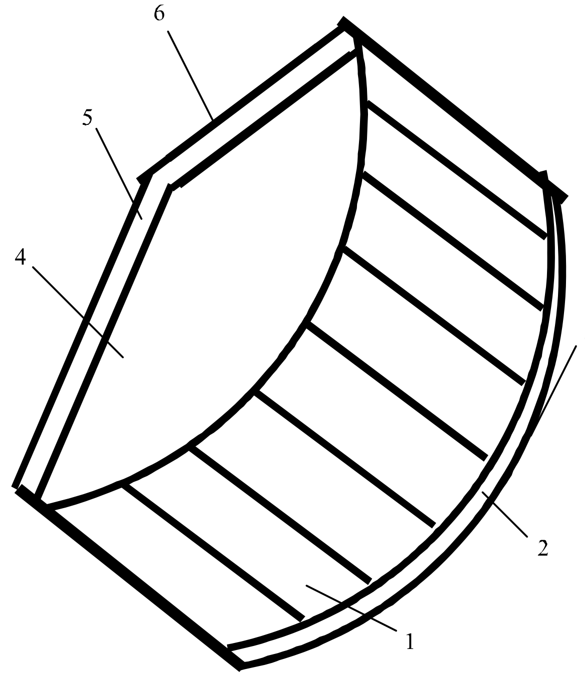
The methane tank was filled up to 70% of volume by organic wastes of the GIK Institute sewage, firstly, and secondly, by sewage (50%) and cow dung (25 and 25% water) as well. In the case of use of cow dung only, the slurry is prepared with 50% of fresh dung and 50% of water. Solar beams penetrating through the inclined glass cover (14, in Fig. 1) are reflected from reflector, penetrate the horizontal glass cover and absorbed by the absorber that is heated and transfer heat to the slurry.

4. RESULTS AND DISCUSSION

The optimal temperature range for psicrophilic, mesophilic and thermophilic bacterias' growth and activity and biogas production is about 20, 35 and 55°C respectively [5]. In the winter period usually the average temperature in biogas digester is lowered that decreases the rate of biogas production but increases the retention period. For analysis of the heating of the slurry by solar energy in the biogas production process the energy balance equation for the case of a static mass of fluid (the slurry's properties is considered as water properties) is being heated may be used [4]:

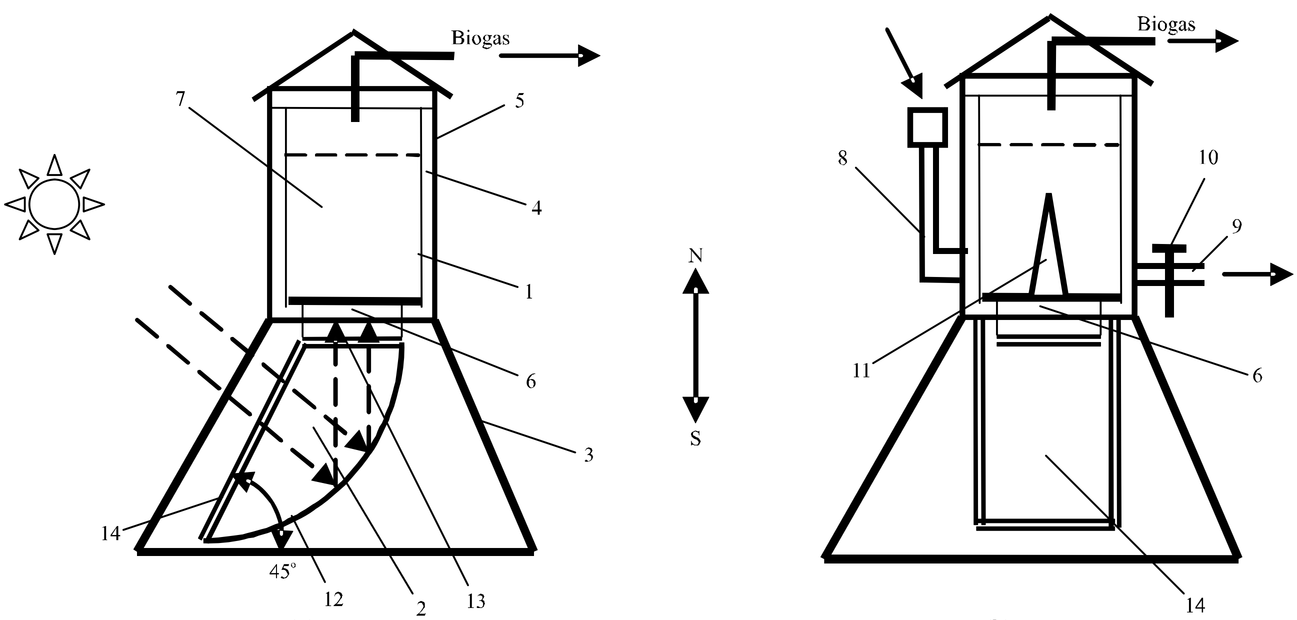
$$mc\, dT_f/dt = \alpha\tau AG - (T_f - T_a)/R \qquad (1)$$

where *m* is mass of slurry, *c* is specific heat capacity, T_f is temperature of the slurry, ? is absorptance of the absorber, α is transmittance of the glass, A is the exposed area of the absorber, *G* is the global irradiance on the inclined glass cover, T_a is ambient temperature and *R* is thermal



(1) THE PLANE MIRROR STRIPS (2) THE PLASTIC SHEET (3) THE CYLINDRICAL METALLIC GROUND (4) THE PLANE MIRROR (5) PLASTIC SHEET (6) PLANE METALLIC SHEET

FIG. 2. THE CYLINDRICAL REFLECTING MIRROR OF SOLAR REVERSE ABSORBER HEATER



(a) *(b)*

(1) CYLINDRICAL PLASTIC METHANE TANK (2) A REVERSE ABSORBER HEATER (3) A PYRAMIDAL SUPPORT (4) THERMO INSULATING MATERIAL (5) ALUMINUM FOIL (6) THE METALLIC ABSORBER (7) SLURRY (8) INLET(9) THE OUTLET (10) TAP (11) THE PARTITION (12) THE HORIZONTAL AXES, CYLINDRICAL REFLECTING MIRROR (13) AND HORIZONTAL GLASS COVER (14) THE INCLINED GLASS COVER

FIG. 1. THE BIOGAS DIGESTER WITH BUILT-IN SOLAR REVERSE ABSORBER HEATER

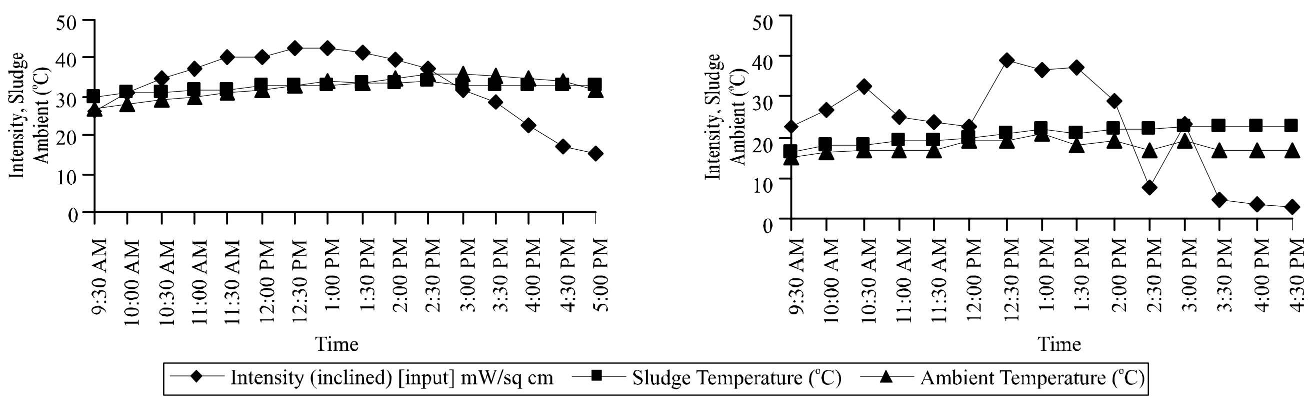
resistance to heat loss from absorber-slurry system to the outside environment. The thermal resistance *R* reflects all heat losses due to the thermal conductance of insulating layer of the methane tank, convection and radiation from the surface of methane tank, evaporation of the slurry inside of the methane tank (evaporated water partly condensed after releasing its latent heat and partly is moved by biogas), and by RAH. As in the RAH convection and radiation losses inside of it are minimized,

FIG. 3. FABRICATED SOLAR BIOGAS DIGESTER WITH FLEXIBLE GAS-HOLDER

and practically may be neglected. Thus it may be assumed that mainly heat losses are due to methane tank's thermal insulator. Taking as a main parameter the maximum temperature of slurry inside of the methane tank to 50°C that is close to thermophilic bacterias' growth and activity, using Equation (1), the thermal resistance can be determined to be R=0.33 K/W, for the case when α=0.9, τ=0.81, for two glass layers of A=0.5m^2, G=250W/m^2, at the mean annual irradiance, and T_a=20°C and taking into account the maximum temperature of the slurry dT_f/d_t=0. Thermal resistance (R) of the heat conductance given in [5] is as:

$$R = \Delta x/k\,A_m \qquad (2)$$

where *k* is thermal conductivity, A_m is the area of the side surface and lid of the methane tank, we can determine the thickness of thermo insulating material (Δx). The thickness of thermo insulating material would be equal to 10cm if a thermo insulating material such as glass wool be used. Fig. 4(a-b) shows solar irradiance, slurry's temperature and ambient temperature-time relationships obtained for the one day in October, 2009 (Fig. 4(a)) and March, 2010 (Fig. 4(b)). It is seen that initially T_a>T_f but starting from the noon time, where solar irradiance is the maximum, the slurry's temperature prevails over the ambient temperature.



(a) (b)

FIG. 4. SOLAR IRRADIANCE (MW/cm^2), AMBIENT TEMPERATURE (°C) AND SLURRY TEMPERATURE (°C) VERSUS TIME FOR ONE DAY IN OCTOBER, 2009 (FIG. 4(a)) AND MARCH, 2010 (FIG. 4(b))

5. METHOD OF ENERGY CALCULATION

The optimal temperature range for psicrophilic, mesophilic and thermophilic bacterias' growth activity and biogas production is about 20, 35 and 55°C respectively [5]. It is assumed that due to heating of the slurry by solar energy, the average temperature inside of methane tank is in optimal domain. Daily produced biogas amount, and electric power that may be obtained from this biogas is calculated.

The volume of fluid $V_f = 0.7\, V_d = 0.56\, m^3$ ($V_d = 0.8\, m^3$ is volume of methane tank).

The mass of dry input m_o is [5] calculated as:

$$m_c = V_f \cdot \rho_m = 28\ kg \tag{3}$$

Considering $\rho_m \sim 50\ kg\ m^{-3}$ [5]

The biogas volume calculated $V_b = cm_o = 8.4\ m^3$ (4)

c is the biogas yield per unit dry mass (0.2-0.4 m^3kg^{-1})

The energy of biogas E is calculated from [5] is:

$$E = \eta H_m f_m V_b \tag{5}$$

Where η is combustion efficiency (`60%), Hm is a heat of combustion (20 MJm^{-3} at 0.01 atmosphere), f_m is fraction of methane in biogas (~0.7). We have obtained E=70.6 MJ.

Assuming retention time t_r=20 days, daily produced energy E_{de} by the biogas digester is calculated as:

$$E_{de} = E/t_r = 3.5\ MJ = 0.97\ kWh \tag{6}$$

If this energy is used daily two hours then the power P_e of generator for conversion of biogas energy into electricity will be almost 0.48 kW.

Digester produces daily 0.4m^3 of biogas.

Practically it was found that using sewage only and sewage with cow dung the retention times was 4 weeks and two weeks respectively and biogas quantity produced daily was 0.2 and 0.3 m^3 respectively during one to two weeks without feeding by the slurry.

Before the use of the biogas in the generator it is desirable to upgrade it by water scrubbing [6] that increases the concentration of methane in biogas up-to 88-98%. For this purpose the compressor of 100-200W is needed for pumping of biogas through absorption tower. For the production of electric power, fueled by the natural gas, generators can be used.

6. BIOGAS UPGRADING AND UTILIZATION

To use biogas directly is simple and cheap, but it is acceptable mostly for heating and cooking if concentration of H_2S is sufficiently low. The biogas pressure in this case should be around of 8-25 mbar. To avoid corrosion due to the presence of H_2S, it is recommended to use chimneys made from stainless steel or high temperature resistant plastic. It is recommended to remove water vapor from raw biogas. In this process H_2S is also removed partly. In the case of use of biogas as a vehicle fuel or natural gas in the present grid the quality of biogas should be improved or upgraded [6]. For this the concentration of methane be increased and carbon dioxide, H_2S, water, particles etc. be removed. Upgraded biogas will have a higher calorific value, constant gas quality, does not have mechanical particles, and does not bring to corrosion and ice-clogging due to the presence of water. Table 1 shows the requirements to remove gaseous components depending on the biogas utilization.

CHP (Combined Heat and Power) engine may be an internal combustion engines, a spark ignition engine or a diesel engine. In the last case it will work as a dual fuel engine. Efficiencies of these engines are 29% (for spark engine) and 31% (for diesel engine). One of the good applications of biogas is in the gas turbines for electric power generation, but the efficiency of turbines is sufficiently high at greater powers of around of 800kW. Table 1 show that the up gradation of biogas is important first of all for its use as the vehicle fuel and as a natural gas for the grid.

For carbon dioxide removal several methods such as water absorption, polyethylene glycol absorption, carbon molecular sieves and membrane separation were developed. Water scrubbing is the most simple and cheap, and is used to remove CO_2 and H_2S from biogas because these gases are soluble in water more than CH_4. Fig. 5 shows the removal of carbon dioxide and/or hydrogen sulphide from biogas and then its compression. The absorption is a physical process. The absorption tower is one of the important parts of the water scrubbing technology. Biogas under pressure is fed from the bottom of the tower whereas; water under pressure is fed from the top of the tower. The used water is regenerated in desorption tower by de-pressurizing or by stripping with air. The cheap method is to use water without its recirculation and for this for example; water from a sewage treatment plant is available. As it is seen from Fig. 6 that the rectified biogas is used for the generation of electric power that in turn is used to feed compressors, pumps and any other load. Extra gas is compressed and bottled for the use in the vehicles, generators etc.

Polyethylene glycol or Selexol is a trade name and is used for scrubbing; such as for water because it dissolve CO_2 and H_2S better than the water. In comparison to water, using Selexol the demand for the amount of solvent is less. In the case of Selexol absorption process, recirculation is used.

From coke with micro-range porous, molecular sieve is produced [5]. Molecular sieves separate selectively some gases from the mixture of gases. The different mesh sizes and/or different applied pressure provide the selectivity properties under absorption process; such as if the pressure is decreases the absorbed gas is desorbed.

TABLE 1. REQUIREMENTS TO REMOVE GASEOUS COMPONENTS DEPENDING ON THE BIOGAS UTILIZATION

Application	H_2S	CO_2	H_2O
Gas Heater (Boiler)	<1 ppm	No	No
Kitchen Stove	Yes	No	No
Stationary Engine (Combined Heat & Power Engine)	<1 ppm	No	No Consideration
Vehicle Fuel	Yes	Recommended	Yes
Natural Gas Grid	Yes	Yes	Yes

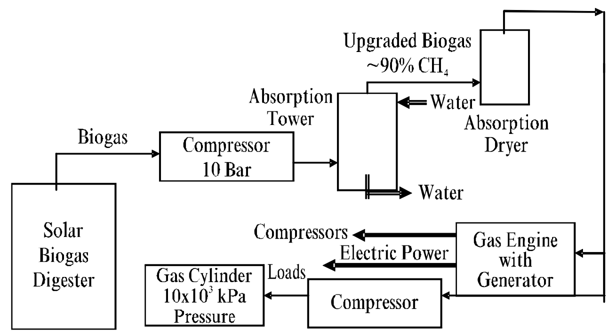
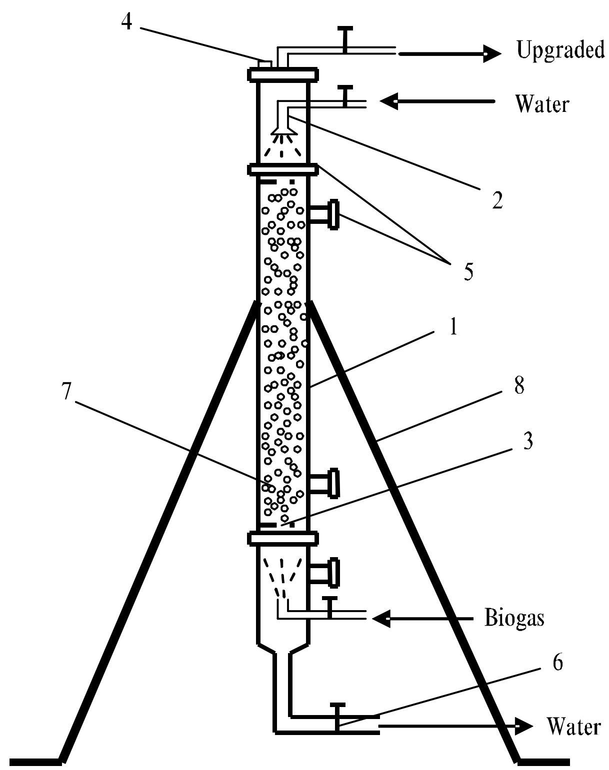


FIG. 5. REMOVAL OF CARBON DIOXIDE, HYDROGEN SULPHIDE AND WATER FROM BIOGAS AND CONVERSION OF ITS ENERGY INTO ELECTRIC POWER AND COMPRESSION



(1) TOWER (2) SHOWER FOR WATER SPRAY (3) METALLIC PLATE WITH PORES TO HOLD PACKING (4) PRESSURE SAFETY VALVE (5) FLANGES (6) VALVE (7) CERAMIC PACKING MATERIAL (DIAMETER=25mm), 8. STAND

FIG. 6. SCHEMATIC DIAGRAM OF THE ABSORPTION TOWER

Membranes are used for gas separations under high and low pressure systems. In the case of high pressure system; the gas under a pressure of 36bar is cleaned by activated carbon to remove halogenated hydrocarbons, hydrogen sulphide and oil vapor from compressors. After this, gas passes a particle filter and a heater. The acetate-cellulose is used for the fabrication of membranes. The membranes separate small polar molecules as CO_2, H_2O and H_2S, but cannot separate nitrogen from biogas. For low pressure system (pressure is ~1bar); gas-liquid absorption membranes were developed recently: micro porous hydrophobic membrane separates the gaseous phase from the liquid phase. The biogas molecules from the gas phase side flows through the membrane to the liquid side that in turn flow in the direction of membrane's plane and are absorbed. Coral or NaOH are used as absorbent. This system is cost effective and efficient from the point of the removal of CO_2 and H_2S. As H_2S is a very reactive matter, the removal of it is an important task and a number of methods are developed including; air/oxygen or iron chloride addition to biogas or slurry, use of iron sponge, iron oxide pellets, activated carbon, water scrubbing, NaOH scrubbing, biological removal on filter bed, air stripping and recovery. Table 2 shows biogas upgrading and utilization in some European countries and USA. From Table 2, it is seen that water scrubbing is the most popular method for the removal of CO_2 and H_2S from biogas.

Water removal is realized by: (i) condensation method, (ii) drying method and (iii) absorption of the gas to silica. The condensation method simply can be realized by using water taps in the gas pipe. Usually the water removal by this method is sufficient for gas that be used in the engine. In the drying method the biogas should be cooled. In the result it entrapped in the demister. The absorption dryer allows achieving high level of water removal from biogas. For these purpose two columns filled by silica is used in sequence: one column is connected to biogas pipeline system for drying of the biogas, the second column is regenerated by heating in opened conditions. Fig. 7 shows schematic diagram of the absorption water dryer.

During experimental work that was done in the autumn and spring times the slurry's temperature didn't exceed 40^{o}C. As in summer time the slurry's temperature can be more than 50^{o}C, therefore a "smart window" is designed for glass cover of the reflecting mirror based on the Venetian blind regulated by temperature control system, firstly and secondly, thermochromic coating based on vanadium oxide. These measures allow providing effective temperature dependent controlled shading of the reflecting mirror.

Table 2 shows the main applications of biogas. At the same time biogas energy can be converted into electric

TABLE 2. BIOGAS UPGRADING AND UTILIZATION IN EUROPE AND USA

Country	Biogas Utilization	Biogas Production	CH_4 Require (%)	CO_2 Removal Technique	H_2S Removal Technique	In Operation Since
Czech. Rep.	Vehicle Fuel	Sewage Sludge	95	Water Scrubbing	Water Scrubbing	1985
France	Vehicle Fuel	Sewage Sludge	96.7	Water Scrubbing	Water Scrubbing	1994
Netherlands	Natural Gas	Landfill Green Waste	88	Membranes Carbon Molecular Sieves	Activated Carbon	1991
Sweden	Vehicle Fuel	Sewage Sludge Vegetable Waste	97	Water Scrubbing Carbon Molecular Sieves	Water Scrubbing Activated Carbon	1992
Switzerland	Vehicle Fuel, Natural Gas	Bio Waste	96	Selexol Scrubbing Membranes Water Scrubbing	Selexol Scrubbing Activated Carbon	1981
USA	Vehicle Fuel, Natural Gas	Landfill Sewage Sludge	98	Selexol Scrubbing Membranes Water Scrubbing	Selexol Scrubbing Activated Carbon	1981

power and heat by fuel cells. The biogas output may be increased by increasing the number of units of the biogas digesters. This biogas digester may be used domestically as well as for the demonstrative or teaching purposes. In addition based on the results achieved it can be used for the construction of larger volume digesters for use in the farms, especially located in the remote and mountain areas where the climate in the winter period is cold.

7. CONCLUSION

The biogas digester with built-in solar reverse absorber heater is presented where reverse absorber heater is installed under the methane tank. The temperature of the slurry-solar irradiance and ambient temperature relationships experimentally were investigated. The biogas up gradation scheme for removal of carbon dioxide, hydrogen sulphide and water vapor from biogas and conversion of biogas energy conversion into electric power are discussed.

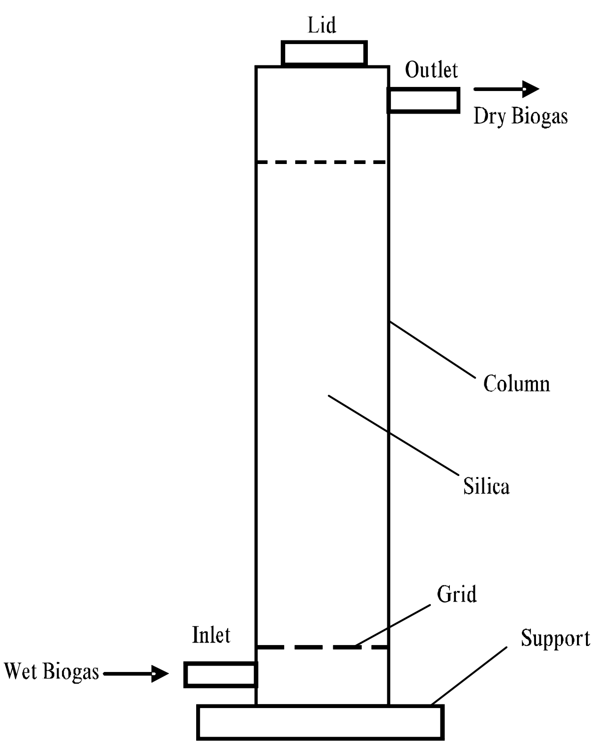


FIG. 7. SCHEMATIC DIAGRAM OF THE ABSORPTION WATER DRYER

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