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Development of a small-scale trigeneration plant based on a CI engine fuelled by neat non-edible plant oil

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This study presents design and construction of a tri-generation system (thermal efficiency, 63%), powered by neat non-edible plant oils (jatropha, pongamia and jojoba oil or standard diesel fuel), besides studies on plant performance and economics. Proposed plant consumes fuel (3 l/h) and produce ice (40 kg/h) by means of an adsorption refrigerator powered from the engine waste jacket water heat. Potential savings in green house gas (GHG) emissions of trigeneration system in comparison to co-generation (or single generation) has also been discussed.

Keywords: Adsorption cooling, Biofuels, CI engine, GHG emission, Performance, Trigeneration

Introduction

Biofuels produced from renewable biomass resources are considered as a favourable option to mitigate greenhouse gas (GHG) emissions and also as a sustainable substitute to rapidly depleting fossil fuels. Global energy demand is increasing rapidly due to upward trend in population and growth in per capita consumption; it is forecasted that energy demand in 2100 will be five times greater than today[1]. Achieving higher conversion efficiency, and reductions in GHG emissions and capital investment cost can be met from one single plant using only one single fuel input. Trigeneration (simultaneous generation of electricity, cooling/airconditioning and heating/other energy services) system (TS), which presents many advantages over co-generation or single generation plant, using fossil fuels already exist, but most of these are medium to large scale systems[2-6]. Deng *et al*[7] reviewed TS combined with thermally activated refrigeration units based mainly on absorption, adsorption and desiccant cooling techniques. A small scale (12 kW) gas engine generator coupled with 10 kW adsorption chiller[3] (working fluid, silica gel-water; coefficient of performance (COP), 0.3-0.4) and a waste heat recovery system was set up at Shanghai Jiao Tang University, China. SorTech[8] developed a compact small scale adsorption chiller (silica gel-water), driven by hot water (55-95°C). SorTech[8] also developed adsorption cooling machines (capacity, 8 kW & 15 kW), which can produce chilled water at 10°C. Buckes *et al*[4] coupled SorTech chiller with a micro CHP system and observed that longer cycle time gives higher COP and less cooling power. Small-scale CI engine-based TSs coupled with vapour absorption has been investigated for remote/rural area application[9,10]; overall efficiency[9] of one such plant reached to 86.2%. Development of TS (thermal efficiency, 60%) with a gas engine and an ejector cooling cycle is also reported[11]. Development of a small scale gas engine-adsorption chillier (silica gel-water type) based TS is reported[12] to generate (COP, 0.3), and produce electricity (12 kW), heating load (28 kW) and cooling load (9 kW). Overall energy efficiency of TSs typically ranges 70-90%[3,12]. Solar-energy based adsorption cooling is also reported[13-15].

This study presents a small-scale TS running on non-edible neat plant oils (or fossil diesel) based on a standard CI engine, engine waste heat driven adsorption cooling m/c, preheating arrangement of plant oil, and heat recovery units for cooking/steam generation application (Fig. 1) and control systems.

Experimentation and Results

Trigeneration: Principles and Technical Specification

A Lister Petter Alpha model LPWS3 engine (rated capacity, 9.9 kW at 1500 rpm; conversion

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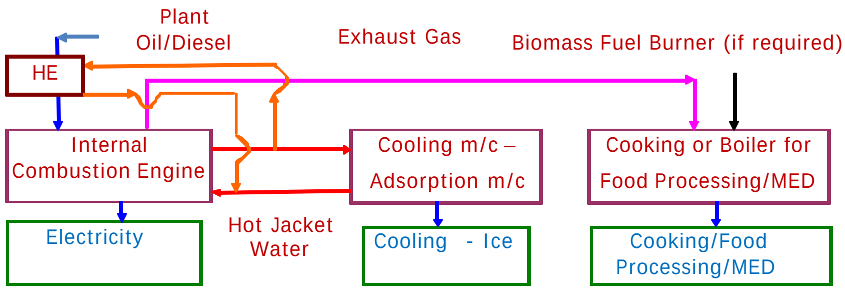

Fig. 1—Simplified layout of non-edible plant oil fuelled trigeneration system

Table 1—Properties of non-edible plant oils and fossil diesel

Property	Neat jatropha oil	Neat karanj oil	Neat jojoba oil	Diesel
Kinematic viscosity$^{25°C}$, cSt	56.01	79.21	37.24	3.97
Pour point temp., °C	-6.05	-7.65	-	-6.17
Cetane Number	44.6	45.6	46.7	50.2
Filterability temp., °C	-7.2	-	-	-8.03
Flash point temp., °C	245	257	184	70
Density$^{20°C}$, kg/m^3	896	929	866	866
Gross calorific value, MJ/kg	38.80	39.20	43.25	44.67

efficiency for single generation, 35%) of indirect injection type was used. Engine exhaust gas and jacket water take 26% and 29% of total input energy respectively[16]; remaining energy (10%) is accounted for by radiation and frictional losses. Overall efficiency of the system can be increased greatly if waste heat, in the form of cooling water and exhaust gas, can be converted into other energy forms. The flow rate of engine jacket water pump is 33 l/min (at 1500 rpm) with an outlet temperature of 99-102°C when thermostat is fully open[16]. At rated load, typical exhaust gas temperature is 420°C and flow 41.4 l/s. Low-grade heat energy can also be recovered from lubricating oil cooling circuit of the engine. Use of neat plant oil is reported[17] to give 2-6 times more lifecycle energy benefits and offers higher GHG emission savings than diesel and biodiesel operation. Non-edible neat oils (jatropha, pongamia and jojoba) have been tested in engine and compared the performance, smoke and emission with commercial diesel operation. A modified fuel supply system and oil preheating system was adapted to the engine. Engine exhaust heat can be used for crop/fish drying purposes, cooking, and in small boiler to make steam for food processing/water purification (distillation) purposes. Utilisation of engine exhaust heat for cooking has been demonstrated in the laboratory. For cooling generation, a thermally activated engine hot jacket water adsorption cooling machine driven by carbon-ammonia has been designed and fabricated.

Neat Non-Edible Plant Oil Properties, Engine Performance, Emission and Endurance

Measurement of Properties

Physical properties of plant oils (jatropha, karanj, jojoba) and diesel fuel were measured in the lab (Table 1). A Setaflash Series 3 ‘Plus’ closed cup flash point tester was used to measure flash point temperatures. A Shatox OPLCM, Shatox Cetane meter and Parr 6100 bomb calorimeter (model 6100) were used to measure pour point temperature, cetane number and calorific values of fuels respectively. A Cannon-Fenski U-tube viscometer was used to measure kinematic viscosity of oils at different temperatures. Neat plant oils have higher viscosity than diesel fuel (Table 1), whereas density, cetane number and calorific values of plant oils are close to diesel values. Viscosity of plant oil can be reduced either by blending with diesel fuel or by pre-heating (Fig. 2) the oil or combination of both. Based on different properties, non-edible plant oils are found to be a potential substitute to diesel fuel in diesel engine for stationary application.

Engine Performance and Emission

A Froude eddy current dynamometer (model AG80HS) was used to measure and adjust engine load and rpm. Engine exhaust emission and smoke were analysed and measured using a BOSCH 5 gas emission analyser (model - BEA 850) and BOSCH smoke opacity meter. A graduated cylindrical tube and a stopwatch were

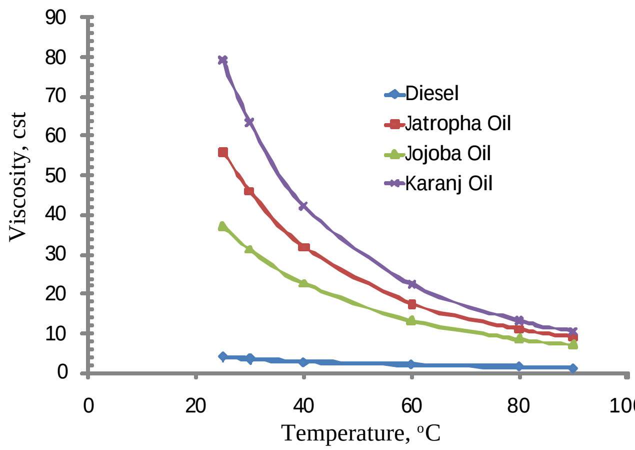

Fig. 2—Viscosity *vs* temperature of neat plant oils at different temperatures as compared to fossil diesel fuel

used to measure fuel consumption rate. LabVIEW data acquisition software was used. To reduce viscosity of plant oils, hot jacket water (partly) from the engine was used to preheat plant oil before injection. A two (2) tank (diesel and plant oil) fuel supply system was designed to flash out plant oils from fuel pipes/injection system. Engine was first started with diesel and then switched to neat plant oils (and blends). Jatropha oil operation shows that power output is almost same for both diesel and plant oil operation. Brake specific fuel consumption (BSFC) of jatropha oil is found higher than that of diesel operation (Fig. 3). Thermal efficiency of jatropha oil for engine operation is 5% less than that of fossil diesel. Carbon di oxide (CO_2) emission and exhaust

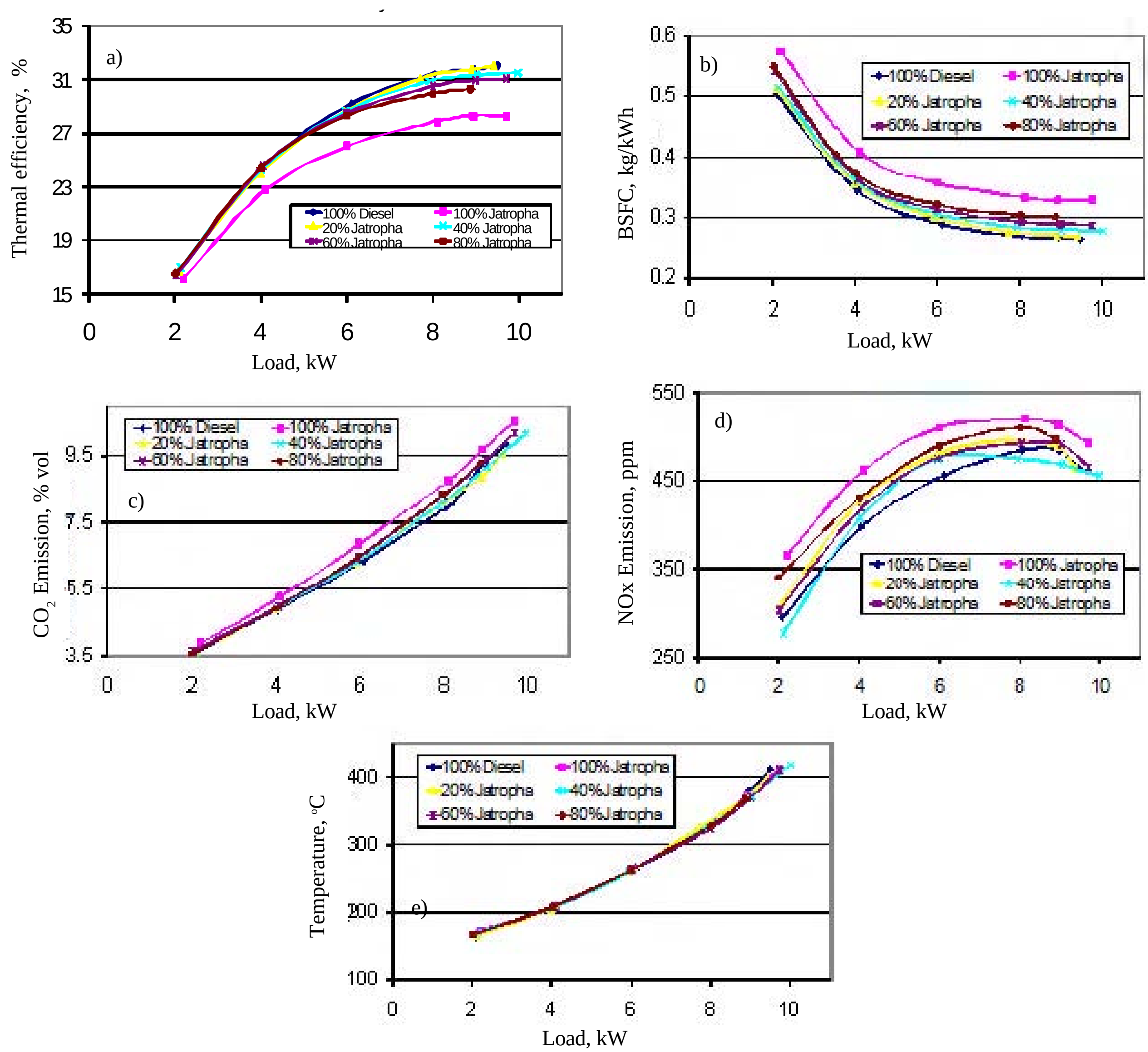

Fig. 3—Performance and emission characteristics of CI engine running on pure Jatropha oil, pure diesel and blends for load *vs*: a) Thermal efficiency; b) Brake specific fuel consumption (BSFC): c) CO_2 emission; b) NOx emission; and e) Exhaust temperature

temperatures are almost same for both jatropha and diesel; but nitrous oxides (NOx) emission is higher for jatropha oil (Fig. 3).

Engine Wear and Tear (Endurance)

Lister Petter engine was operated with neat jatropha oil (and blends) for 30 h. Subsequently, it was necessary to strip down engine for installation of some new instrumentation (cylinder pressure and crank angle sensor), thus giving the opportunity for internal inspection. There was coke formation inside engine cylinder; only small deposits were seen. Injectors were found reasonably clean and in workable conditions; no corrosion or erosion occurred in injectors.

Engine Waste Heat Recovery for Heating and Cooling Applications

Application: Heating

Different types of exhaust gas heat recovery units were designed and tested. An oil heater (Fig. 4) to cook meals and shallow and deep frying was designed, fabricated and tested. Steamer to cook rice and for steaming vegetables and a hot plate to make chapatti were also designed, fabricated and tested. A steamer and two oil heaters were connected directly to engine exhaust pipe with ball valves, so that either one or both can be used simultaneously for cooking purposes. Glass wool insulation was used to prevent heat loss and thermocouple was used to measure temperatures. As waste heat output from engine is directly proportional to engine size, various such cooking accessories can efficiently be used in rural market area/community centres etc. Test results conclude that efficient use of exhaust gas will save a considerable amount of fossil fuel energy and associated GHG emission.

Thermally Activated Adsorption Machine: Cooling

Heat driven cooling machines developed for trigeneration application were absorption chillers, adsorption chillers and desiccant humidifiers. Target of making ice in order to provide storage and easy export of 'coolth' restricts the choice of refrigerant pairs that can be used, eliminating those that use water as a refrigerant. In this study, a carbon-ammonia adsorption refrigerator was developed, designed to be driven by jacket heat from engine and to be suitable for manufacture in India.

Principles of Adsorption Cooling Machine

Ammonia (conc.) on active carbon increases with pressure and falls with rising temperature. Adsorption refrigerator uses four beds of active carbon alternately heated and cooled in a batch cycle. As temperature of the bed being heated increases, ammonia is driven out and flows to condenser. From there, liquid flows to evaporator, where it is re-adsorbed by the bed being cooled. At any point in the cycle, one bed is being heated, one being cooled and two are exchanging heat between each other. Sequencing of heat transfer fluid valves is achieved by a programmable logic controller (PLC).

Fig. 4—Exhaust heat application for preparing meal in community centres or local markets

Design and Construction of Carbon-Ammonia Ice Making Machine

In adsorption refrigerator (Figs 5 & 6), adsorbent beds (1.2 m long, 130 mm diam) are constructed of active carbon packed between aluminium fins (500 are needed per machine) that are in turn attached to tubes carrying heat transfer fluid. This relatively simple construction allows good heat transfer within the bed. Fins (£1 each) were made by Britannia heat transfer using Elfin system (Fig. 5). Shell is made from perforated steel (0.6 mm holes at 1 mm pitch). Whole assembly has been placed in a pressure vessel. Each bed contains 7.25 kg of active carbon (Fig. 7). In order to be able to produce ice in areas of high ambient temperatures while using a relatively low temperature heat source, ice maker can work in a two stage configuration where beds work in pairs, a low pressure cycle feeding refrigerant to a high pressure cycle (Fig. 6A). Switching from single to two stage configuration requires only the operation of two 3-port valves. Sequencing of heat transfer flow valves is achieved by a PLC.

Ice Maker Performance

In laboratory tests, with a driving temperature of 95°C and rejecting heat at 30°C, ice-maker cooled at evaporating temperatures down to -20°C. However, power of machine was lower than predicted by either

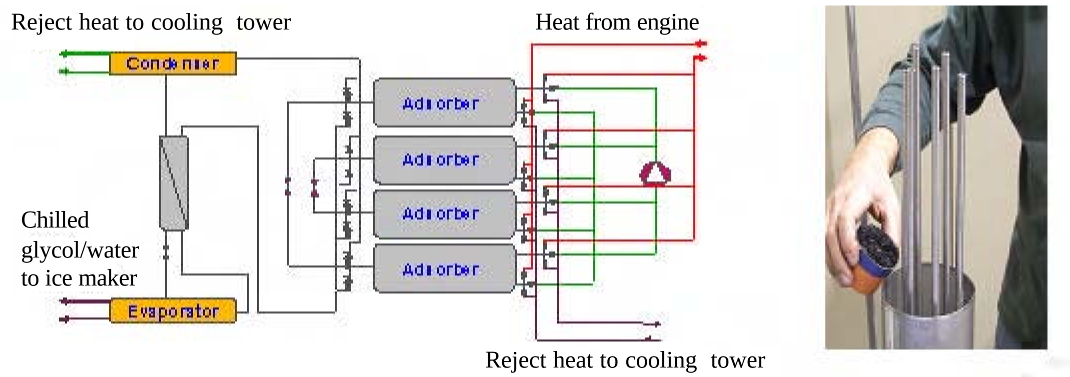

Fig. 5—Adsorption cooling machine: design layout and generator packing with carbon

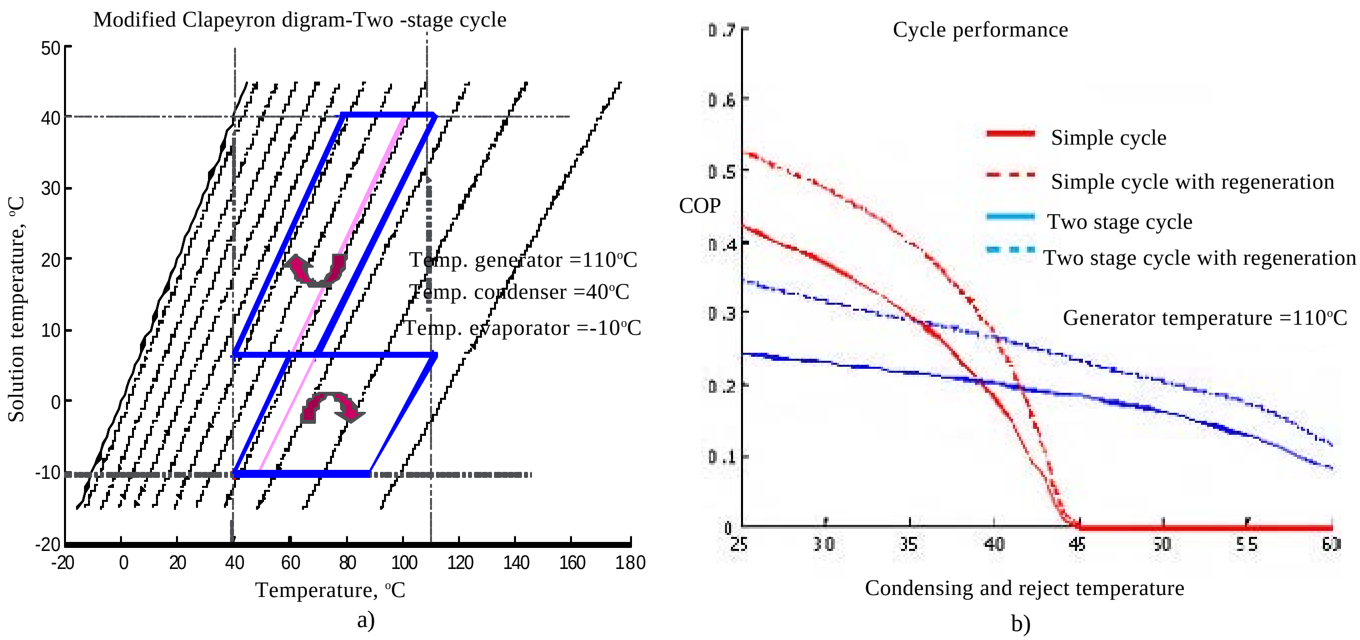

Fig. 6— a) Two stage adsorption cycle; and 6 b) Performance predictions

the detailed model or simpler analysis. Although machine achieved a reasonable internal COP, cooling power was low at 0.3 kW, due to a lower than expected thermal conductivity in packed bed and possibly by poor thermal contact between fins and tubes. Technical issues during operation were reliability and corrosion problems in non-return valves of evaporator circuit, where water was present. In condenser circuit, after removal of an internal damper, they worked reasonably well.

Trigeneration System Performance

Use of engine waste heat for cooling and heating generation alongside with electricity application would definitely increase thermal efficiency, reduce energy consumption and reduce GHG emission significantly. Overall energy ratio (OER) or thermal efficiency of a TS is given as OER = (heating load + cooling load + electrical load)/(energy of plant oil + electricity needed to operate the fan/pump). For present system, values were as follows: electrical load, 9.9; cooling load, 4; and heating load, 4.5 kW (based on Fig. 7 and assuming 60% waste heat recovery for heating application). On this basis, OER or overall thermal efficiency of TS is 63%. As engine waste heat was used for cooling and heating generation, so substantial GHG savings are possible, if these services were to be provided by separate units. Centralised TS also increases reliability of energy supply services. Due to the combination of multiple generations, TS offers cost reduction as a whole, including savings in fuel costs, infrastructure (land and buildings), operator costs, and transmission and distribution costs. As a result, payback period of proposed small scale TS will not be long. Silica gel-water adsorption system developed in China reported a payback period of 1.7 - 3.2 y (depending on the type of end use)[3].

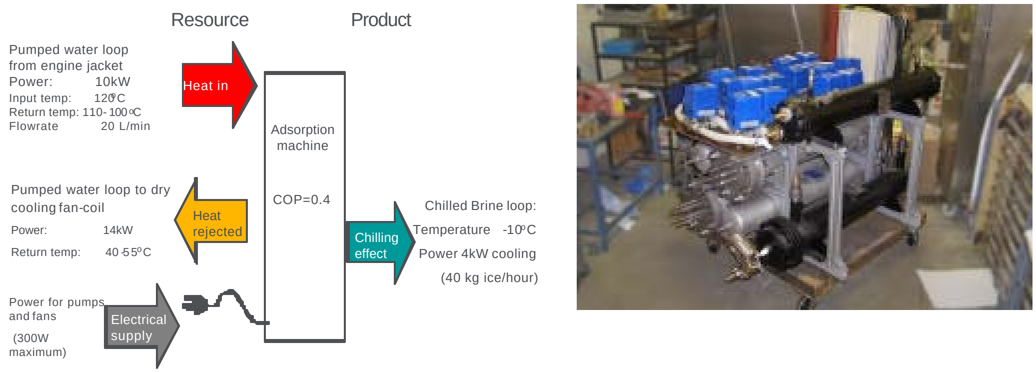

Fig. 7—Cooling power prediction and assembly of machine

Conclusions

This study demonstrates that TS is possible using variety of locally available non-edible pure plant oils without depending on imported petroleum fuels; instead local services can be provided with locally available fuels. Jatropha, karanj and jojoba oils are non-edible and also can be grown in wastelands and in dry areas using wastewater. Using waste heat to get cooling and heating effect makes the whole system highly efficient and also reduces GHG emission substantially (which would have occurred if separate machines were used to get these services) and overall capital investment costs considerably. Poor power density of carbon-ammonia system, demonstrated in this study, can be improved by decreasing fin pitch in generators and using a monolithic carbon made from granular material with a binder. Machine can be simplified by use of custom made valves rather than 16 3-way valves in current device. Further, simplification and cost reduction could be made by the use of a machine with no thermal regeneration, although COP would be reduced. Two-stage cycle extends useful operating range significantly and could be easily incorporated in such a design.

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