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ADVANCED ENERGY CONVERSION TO POWER

NOAM LIOR

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104-6315, U.S.A.

Abstract—This paper reviews some leading novel energy conversion approaches which are aimed at improving power generation efficiency and/or reducing harmful emissions. Some of the concepts used for cycle improvement are higher top temperatures, improved combustion systems, evasion of the Carnot limit by integration with fuel cells and direct nuclear energy conversion to power (the nuclear generator), reduction of exergy destruction by staging and the use of exergy-efficient combustion processes, the use of lower temperature heat sinks and the use of renewable, environmentally-benign energy sources. Some of the systems described in this paper are hybrid multi-temperature source cycles (including the hybrid solar-powered/fuel-assisted Rankine cycle), high-temperature chemical gas turbine cycles, fuel-cell-topped Rankine cycles, high temperature ejector-topping power cycles and hybrid nuclear/fossil fuel power generation systems. The use of space (the extra-terrestrial environment) for energy conversion improvement is also discussed. © 1997 Elsevier Science Ltd.

Power generation   Energy conversion   Fuel cells   Nuclear power   Renewable energy
Pollution   Combustion   Space power

NOMENCLATURE

A = Exergy (kJ/kgmole)
g = Gibbs function (kJ/kgmole)
P = Pressure (kPa)
$\dot{R}$ = Process rate (kgmole/s)
$\Re$ = Universal gas constant (kJ/(kgmole·K))
S = Entropy (kJ/(kgmole·K))
t = Time (s)
T = Temperature (K)

Greek symbols

λ = Reaction affinity (kJ/kgmole)
μ = Chemical potential (kJ/kgmole)
ε = Heat flux (kJ/m²s)
η_C = Carnot power cycle efficiency
χ = Mole fraction

Subscripts

c = Cold
d = Destruction
f = Fuel
h = Hot
I = Of species I
o = Reference state
p = Production

Superscripts

$\dot{}$ = Per unit time

1. INTRODUCTION

1.1. *Scope*

Energy conversion systems are advanced if they improve upon conventional ones. The improvements may be in one or several categories: higher energy and/or exergy efficiency, lower energy and/or species emissions, lower capital cost, lower operating costs or required expertise and higher reliability. Obviously, improvements in some categories should not cause unacceptable deterioration in others, and synergistic improvements where an improvement in one category results also in improvements in other categories are the most desirable. For example, increasing efficiency also reduces energy emissions to the environment.

This paper reviews some leading novel energy conversion approaches which are aimed at improving power generation efficiency and/or reducing harmful emissions, in large part based on work by the author and his co-workers. Some of the concepts used for cycle improvement are higher top temperatures, improved combustion systems, evasion of the Carnot limit by integration with fuel cells and direct nuclear energy conversion to power (the nuclear generator), reduction of exergy destruction by staging and the use of exergy-efficient combustion processes, the use of lower temperature heat sinks and the use of renewable, environmentally-benign energy sources.

1.2. *Energy conversion efficiency*

Power generation terminology typically defines the process efficiency in terms of energy, partially due to traditional reasons and partially because process inputs, such as fuel, are still costed based on their energy (usually heat) value. At the same time it is increasingly realized that the true measure of power generation efficiency is the exergy efficiency, which relates the work output to the maximal useful work value of the input [1, 2].

For a given thermodynamic state of a system and given energy or exergy inputs during a process in which one or more constraints on the system were removed, the maximal amount of work will be produced in a reversible process. Such processes are characterized by infinitesimally small thermodynamic driving forces and negligible dissipation (internal entropy generation), and therefore lead, unfortunately, to either infinitesimally low process (including power generation) rates, or infinitely large process hardware requirements. Practicality, therefore, allows some irreversibility in the process and thermodynamically maximal energy or exergy conversion efficiencies cannot be attained, but R & D has, is and should be conducted to approach them closer and closer. Detailed exergy (or second-law) analysis indeed serves well in that effort since it alone can identify the specific irreversibilities.

The maximal efficiency η_C of energy conversion processes which occur due to heat flow is defined by the Carnot limit

$$\eta_C = 1 - \frac{T_c}{T_h} \tag{1}$$

where T_c and T_h are the absolute temperatures of the cold heat sink and the hot heat source for the power cycle, respectively. This limit is simply the expression of reversibility in a thermal energy conversion process. Although only a guide for practical power generation efficiency, equation (1) clearly indicates the desirability of increasing the heat source temperature and decreasing that of the heat sink.

Energy conversion processes which do not occur due to heat transfer are not limited by the Carnot efficiency, but by process irreversibilities.

2. THE ENVIRONMENTAL REACTION TO POWER GENERATION

2.1. *Energy conversion species emissions*

Conventional power generation processes are accompanied by the emission of species into the environment, with associated detrimental effects. Such emissions occur during the fuel extraction, transportation and conversion phases and may produce secondary emissions of their own as they deposit in the environment or are stored somewhere. They consist of a variety of species, ranging from radioactive materials, some of which, such as plutonium, have half-lives of tens of thousands of years, hydrocarbon, inorganic and inert gases, liquid hydrocarbons and solutes in water (such as coal mine drainage), and various combustion products. Prevalent among the latter is CO_2, which until recently was thought to be harmless and has then been found to have major effect on global warming. Perhaps one of the least harmful emissions is that of water vapor, which is the primary emission when H_2 is used as the fuel.

Solar and lunar energy power generation processes probably emit the least amount of species, confined to emissions associated with the processes used to make the materials and manufacture the system components and to chemical decomposition of these materials during the operation of the power generation system.

2.2. *Energy conversion energy emissions*

Any of the energy input into a power generation system which does not get converted into useful work ends up as heat, which in a steady-state process is discarded into the environment if unused. It is consequently important to note that high efficiency is not only rewarding from the power output standpoint, but it also reduces the thermal burden on the environment.

Although such energy emissions mostly end up ultimately as heat, they in many cases have other environmentally detrimental effects during their transformation into heat. For example, although constituting only a small fraction of the discarded energy, radiative emissions from nuclear power plants, such as neutrons and α particles and γ rays, as well as strong electric fields emitted by electrical power generation and transmission equipment, may cause harm significantly beyond their energy content.

3. RAISING THE TOP TEMPERATURE

Most energy sources are not in principle limited by the temperature to which they can elevate the working fluid of the power generation cycle. This is operationally obvious in fuel combustion systems and nuclear fission or fusion systems, but is even true for diffuse sources such as solar energy: temperatures of thousands of degrees have already been attained with existing concentrators. Increasing the efficiency of thermal power generation cycles by raising the top temperature is, thus, not constrained by the potential of the energy source to do so, but is constrained by the ability of engineering materials and devices to withstand higher temperatures, sometimes accompanied also by higher pressure and other effects detrimental to the ability of the device to perform its function.

Much progress has been made during the past century in raising the top temperature of the working fluids. This was achieved by a combination of better materials and more ingenious device engineering, such as turbine blade cooling, intermittent combustion accompanied by cooling in internal combustion engines and magnetic field confinement of plasmas at temperatures of millions degrees in fusion power experiments. Here we give an example of a proposed power cycle in which higher top temperature can be achieved by incorporation of a device which can tolerate such temperatures because it has no moving parts, is not subjected to high pressures and can thus be constructed from available materials such as graphite, graphite composites or ceramics.

The proposed system is the ejector-topping power cycle proposed by Freedman and Lior [3], described in Fig. 1. The hot gases generated in a furnace at temperatures above the tolerance of available gas turbines are used to compress another gas in an ejector. They are cooled thereby to a level acceptable for use in present day turbines by a process which produces compression work of another gas. From the second-law viewpoint, the straight cooling of combustion gases from the combustion temperature to that acceptable for turbine operation, as practiced in conventional systems, destroys completely the exergy contained between these two temperatures. Here the same cooling is accomplished with concomitant production of useful work, clearly an important exergetic improvement. The ejector, as opposed to turbines, can operate at the very high temperatures because of its inherently simple construction and absence of moving parts, which result in very low mechanical stresses and high reliability.

Although ejectors have relatively low efficiencies, the ejector-based topping cycles may have an overall higher efficiency than that of current turbine-based topping cycles, because of two major advantages: (1) the ejector can tolerate higher temperatures than a turbine, and (2) it could use working fluids which have thermophysical properties superior to those which can be used in turbine topping cycles. The fluids chosen in that study were helium (the secondary fluid) and sodium (as the primary fluid). It is believed that helium is a good choice as a turbine fluid because of its low molecular weight and its high specific heat ratio, although it is harder to compress in the ejector. Sodium was chosen because there is experience in using it in high-temperature energy systems and its thermophysical properties seem to be more promising than those of other candidate materials.

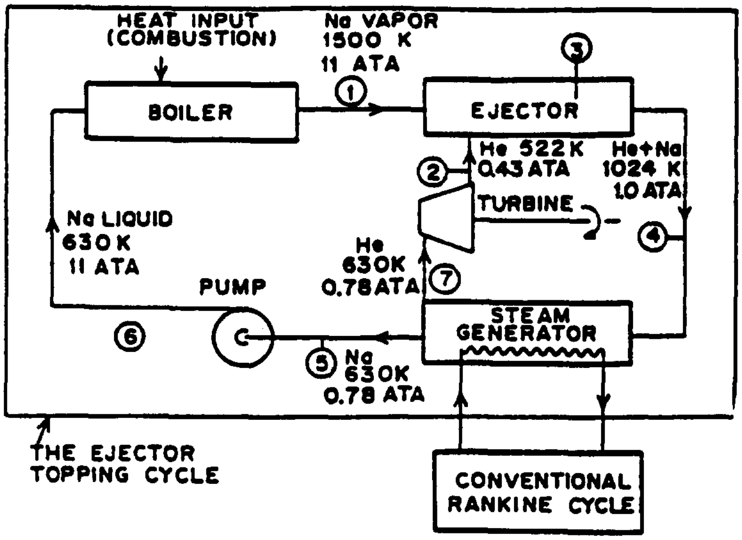

Fig. 1. Flow diagram of an ejector-topping cycle [3].

It is possible that other working fluid pairs are better (and safer relative to sodium) and a thorough thermoeconomic selection study was recommended. A possible material of choice for the ejector is coated or sheathed graphite, as often used in applications such as re-entry vehicles and rocket nozzles. Advanced ceramic materials, are becoming available for continuous operation up to about 2000 K.

A conservative analysis for a 50 MW net output plant with a sodium top temperature of 1500 K and pressure of 1.08 MPa (in the boiler) with the other conditions shown in Fig. 1, has exhibited that this cycle has an efficiency 6.4% higher than a conventional steam Rankine cycle without topping. The improvement was seen to increase to 11% for top sodium conditions of 2000 K, 5 MPa. The bottoming cycle in both cases was a Rankine cycle with exit steam conditions of 810 K, 24 MPa. No attempt was made as yet to optimize the fluids or operating conditions and it is expected that even better efficiency improvements can be attained.

Other improvements were noted in that the high temperature operation allows the use of a much smaller furnace (the sodium boiler) with practically no ash accumulation or emission problems. This holds good promise for coal utilization.

4. IMPROVING LOW TEMPERATURE CYCLE EFFICIENCY BY HIGH-TEMPERATURE SUPERHEAT

There often exist situations where the top cycle temperature is well below the tolerance limit of conventional materials and devices. Some of the examples are solar power systems which use flat-plate or moderately-concentrating collectors, geothermal systems, waste-heat operated systems and water-cooled nuclear reactors where the limitation is due to the accompanying steam pressure and the combined pressure and temperature effects on fuel–rod integrity.

The key to efficiency improvement of such cycles is the well-known fact that the isobars in an enthalpy–entropy (Mollier) diagram (Fig. 2) diverge drastically as the fluid changes from liquid to vapor and continue diverging as the vapor is increasingly superheated. This divergence is the reason why Rankine cycles have an extremely favorable backwork ratio, requiring very little enthalpy increase in the compression of water relative to the steam enthalpy drop during the expansion between the same two isobars in the turbine. Based on this phenomenon, several cycles have been proposed where the steam generated by the primary, low temperature, energy source is further superheated by some other means and then expanded through a turbine to make work.

One example of this is the hybrid solar-powered/fuel-assisted Rankine cycle studied by Lior and co-workers [4, 5] and others [6, 7]. As shown in Figs 2 and 3, the lower temperature (here 102°C) steam generated by solar energy is superheated by passage through an internal heat-recovery heat

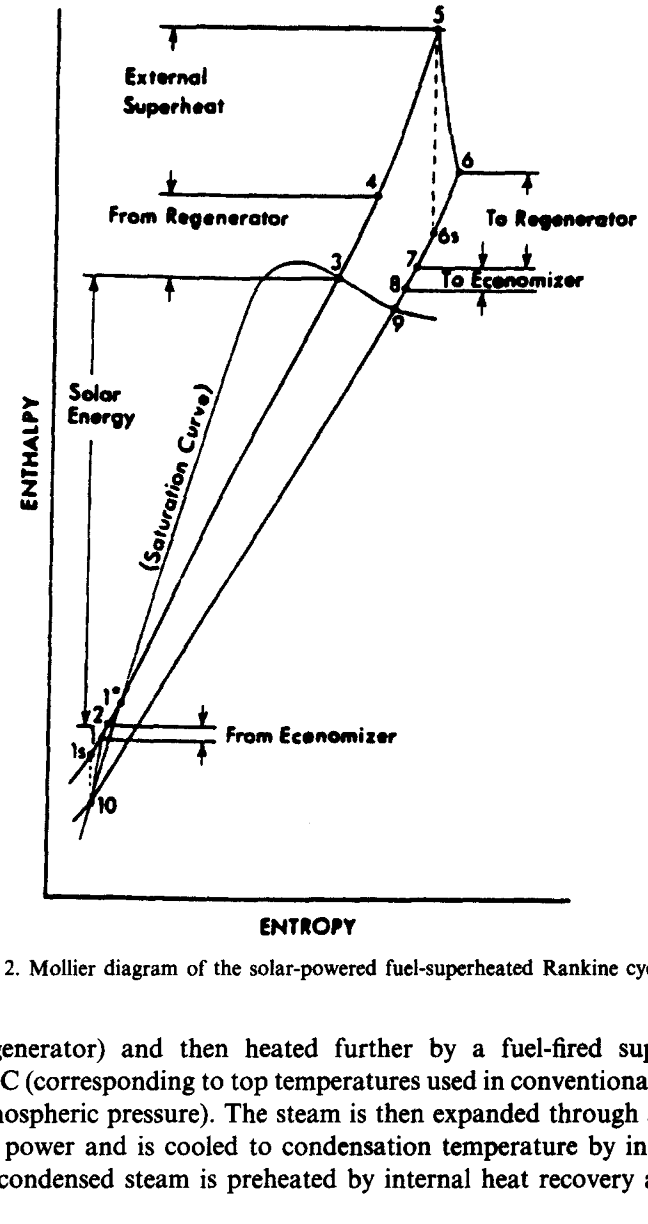

Fig. 2. Mollier diagram of the solar-powered fuel-superheated Rankine cycle [4].

exchanger (the regenerator) and then heated further by a fuel-fired superheater to its top temperature of 600°C (corresponding to top temperatures used in conventional steam power plants, but here at just atmospheric pressure). The steam is then expanded through a low-pressure steam turbine to produce power and is cooled to condensation temperature by internal heat exchange and recovery. The condensed steam is preheated by internal heat recovery and then returned to the solar boiler.

Analysis of the cycle has shown that its efficiency at the above conditions is about 18–20%, more than double that of a power cycle operating at the solar-generated steam temperature of about 100°C, impressively accomplished by the addition from the fuel source of only about 20% of the total energy. A prototype cycle and a 30 hp counter-rotating turbine with an efficiency of 75% were designed and built by the author and his co-workers [4, 5]. Although it requires further proof in larger plants, economic analysis has predicted a clear advantage of such hybrid plants over those operating with the lower temperature heat source only (also see comments in Section 7 about the similar Luz solar power generation system). It is noteworthy that solar energy can also be used to superheat the steam, by employing solar concentrators, thus avoiding the need for fuel.

Similar cycles were also proposed for use with geothermal sources [8] and with automotive engines [9]. Water-cooled nuclear reactors are limited in their top steam temperature and pressure to about 285°C, 6.9 MPa, significantly lower than the 600°C, 30 MPa limits of advanced fossil-fuel fired steam plants. Furthermore, nuclear power plants do not provide superheated steam, while fossil fuel plants do. The efficiency of such nuclear power plants is therefore limited to 29–35%, up to about 1/3 lower than that of advanced fossil fuel power plants. A comparative energy and exergy analysis of an operating BWR power plant [10] has concluded that efficiency can improve by incorporation of a fossil-fuel-fired economizer, superheater and reheater, upstream and downstream of the reactor vessel, respectively. In fact, the Consolidated Edison Company of New York constructed a PWR nuclear station (Indian Point) which incorporated a separate oil-fired superheater, with a resulting 21% gain in efficiency [11]. The cost of produced electricity was found to drop by about one-third when compared to conventional nuclear power plants without fuel superheat. Another externally-superheated nuclear plant using oil for superheating was built near Lingen, Germany, achieving an efficiency improvement of nearly 33% [12]. Neither plant is, however, in operation any longer.

5. LOWERING THE BOTTOM TEMPERATURE

Thermal power plant efficiency increases as the bottom temperature is lowered. In the temperature range of ambient coolants, an efficiency improvement of up to about 1/2% is obtained from each °C by which T_c is lowered. It is thus desirable to seek ways to do so and a few are described below.

One well-trodden path is the improvement of heat transfer in the heat rejection equipment, most prominently in the power plant condenser. This lowers the condensation temperature and pressure of the steam by bringing its temperature closer to that of the coolant. At the same time this approach increases capital costs and pumping energy use.

A most intuitively obvious way to that end is the finding and use of colder coolants. Since power station location is presently dictated in large part by the need for some proximity to the users and by environmental constraints, the selection flexibility as well as the existing differences between the available conventional coolant sources are rather small. At the same time there potentially exist at least three low temperature heat sinks for thermal power plants which deserve consideration: the cold water in the depths of the oceans throughout the world, the cold air, water and ice in the polar regions, and space.

There are many locations around the world, even near the equator, where ocean water temperatures are down to about 5°C at depths below about 500 m. After considering pumping losses, the use of this water for cooling the power plant condenser is expected to raise the plant efficiency by at least 10%. Several experiments of ocean-thermal energy conversion (OTEC) have demonstrated that the construction of the piping system to these depths, and the pumping of the cold water to the surface, are feasible and within reasonable cost. Remaining issues to be more definitively resolved are environmental impact, including effects on the ocean flora and fauna,

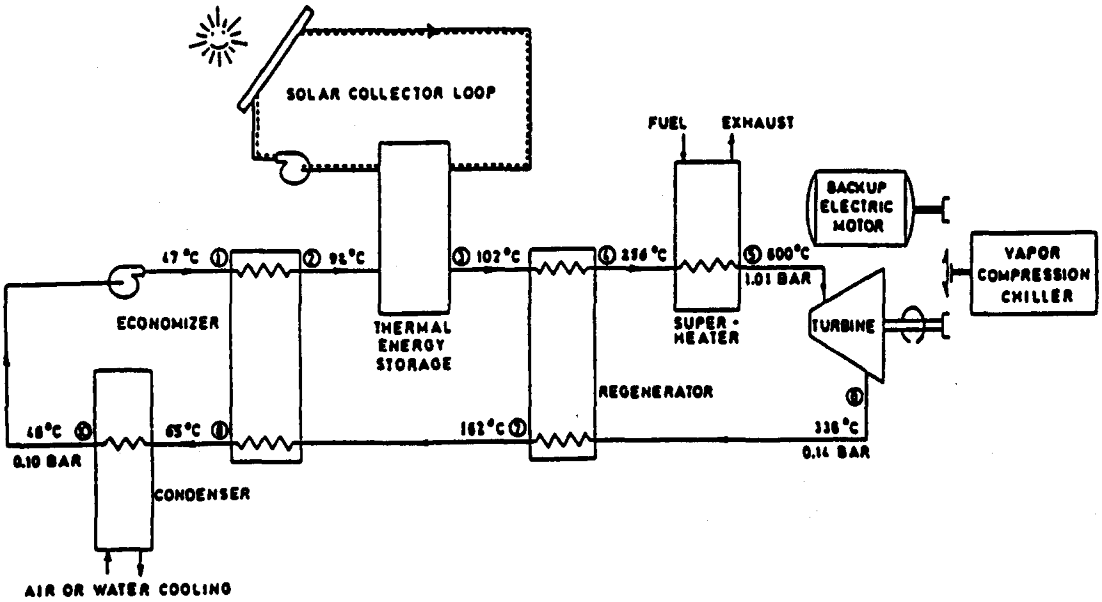

Fig. 3. Flow diagram of the solar-powered/fuel-superheated power system, with typical operating conditions [5].

temperature increase of the ocean water, releases of CO_2 from the water raised to lower pressure surroundings and stability of the piping system under storm conditions.

Power generation efficiency could be significantly increased by using the cold air or ice of the polar regions as coolant. To take full advantage of coolant temperatures much below the freezing point of water, other working fluids would have to be used. In considering this approach, some of the major obstacles are environmental impact and, if fossil fuels are used, the problems of transporting them to such sites.

The use of space as the heat sink for power plant is very appealing. Being at near absolute zero temperature, it is indeed the lowest attainable temperature heat sink. Having immense, and ever expanding, size, it would be affected negligibly by any heat addition from the earth. Diversion of the power-generation related energy emissions from the terrestrial sinks to space would serve well in healing our environment and preventing its further deterioration. The most direct way to affect cooling is by radiative heat transfer from the power plant coolant into space. This is already done in satellite power plants and requires the placement of the power station in space. The difficulties of doing so are obvious, but even the current technology is suitable for this purpose and a side-benefit is the removal of power stations and their detrimental effects from terrestrial locations.

Due to power plant siting requirements, power transmission to user sites is a problem common to all of the above-described ways for reducing the bottom temperature. Super-conducting transmission lines, power transmission by microwaves, or on-site manufacturing of easily transportable fuels for electrochemical or combustive energy conversion are some of the technologies to be explored and advanced for that purpose.

6. CLEANER COMBUSTION

6.1. *Preface*

Many methods are being pursued to obtain combustion which produces lower emissions, especially of the species more hazardous to health. Described here are two approaches in which the author and his co-workers are engaged.

6.2. *The radiatively-conductively stabilized combustor (RCSC)*

In most combustion devices the energy necessary to heat the fuel to the point of ignition is supplied by back-mixing either by molecular or turbulent diffusion. The back-mixing produces an extended reaction zone, contact between the fuel-air mixture and the products of combustion and oscillations. These three side-effects are known to enhance NO_x formation.

A method for stabilizing combustion by radiation and conduction was explored analytically and experimentally by Churchill, Lior and co-workers for many years [13, 14], with gaseous, volatile oil and propane/pulverized-coal mixture fuels. In their studies using fluid fuels, Churchill, Lior and co-workers have demonstrated that extremely low levels of NO_x (5–100 ppm) were generated (a reduction of about an order of magnitude as compared with conventional burners), mostly because of the rapid heating of the fuel and minimal back-mixing of the products of combustion in such burners. This flame stabilization is shown schematically in Fig. 4, where the thermal feedback occurs by radiation from the hot downstream region of the burner to the colder upstream region and also by longitudinal conduction through the tube wall in the same direction. The cold, unburned gases entering the tube are heated to the ignition temperature primarily by convection from the tube wall (but also by convection from the radiantly-heated particles when solid fuels are used). The hot, burned gases, in turn, heat the downstream wall by convection.

When the fuel was pulverized coal, the flame zone was found to be thicker than with fluid fuels, but thin, from about 30 cm near the walls to about 50 cm at the center, relative to conventional pulverized coal combustors. Coal residence times were thus only 0.125 to 0.6 s, smaller than the residence times of about 1 s in commercial combustors using recirculation for flame stabilization, even though the RCSC analyzed here had gas velocities which are about two orders of magnitude slower than those in such commercial combustors. This has the promise of significant reduction in NO_x production.

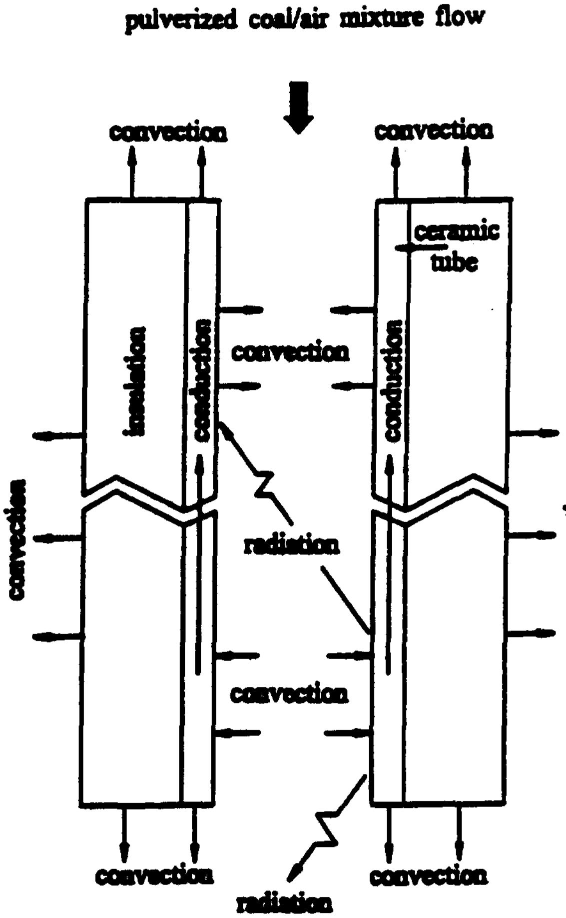

Fig. 4. The thermal feedback mechanism in the radiatively/conductively stabilized combustor [13, 14].

6.3. *The "chemical gas turbine" topping cycle*

To attain high top temperatures and yet low NO_x emissions, Arai *et al.* [15] have proposed a combined Brayton–Rankine cycle (Fig. 5), in which fuel-rich combustion of a mixture of compressed air and fuel takes place in the first burner, the hot gas containing unburned fuel expands through the high temperature turbine, is then recompressed and passed on to a second, lean mixture burner. The gas is then expanded through a lower temperature turbine and then used to generate steam in the boiler of the Rankine cycle. The fuel-rich combustion at the highest temperatures allows good control of NO_x production in that reducing atmosphere. Being below the stoichiometric concentration at which NO_x production is maximal, the fuel-lean combustion in the second combustor also produces only small amounts of NO_x. Because of the possibility of reaction control in the topping part of the cycle, the authors have called it a "chemical gas turbine" cycle.

We have performed an analysis of this cycle and found that the overall efficiency for the conditions listed in Fig. 5 is 62% and the exergy effectiveness is 76%. At optimal circumstances and the same top temperature of 1773 K the efficiency was found to reach 66% with an exergy efficiency of 81%.

7. SOLAR AND LUNAR ENERGY

Solar radiation can be used for direct conversion to electricity, using photovoltaic cells, for thermal plant power generation by converting it into heat, or by its catalytic effect in various photochemical reactions, such as photosynthesis, with subsequent conversion of the biomass to heat. The solar energy input to earth also gives rise to other effects which can be exploited for power generation, such as wind, ocean currents and the ocean temperature differences. The moon produces tides and contributes to wave formation, allowing the use of tidal and wave energy.

In the context of advanced energy conversion, the solar and lunar sources excel particularly in two areas: they are practically inexhaustible, produce minimal species emissions and do not alter the global heat balance. Unless used in thermal power cycles or as combustion fuels, they also have minimal local thermal emissions. At the same time, these sources have a low energy flux and therefore require large areas and a large quantity of material for their use. The components of the plant itself become then a significant consumer of energy and source of emissions in the process of their production and use [16].

Probably the most rapid progress in solar energy conversion technology is seen in photovoltaics, where single cell efficiencies have exceeded 30% in the laboratory. These numbers are approaching power generation efficiencies in conventional nuclear power plants. Improved efficiency, reduced cost and better long-term stability of the cells are the primary objectives of R & D in that field.

Solar thermal power generation was already proven under certain economic circumstances to be commercially competitive in small fuel-superheated plants, such as those manufactured and operated by Luz Co. [17], which have produced electricity at an efficiency of up to 38% at a cost of 8 c/kWh and reliable high-efficiency operation was achieved by a number of large scale central receiver power plants.

8. BEYOND CARNOT

8.1. *Preface*

Power generation schemes which do not need heat as a primary input are not subject to the Carnot efficiency limitations, thus relieving the obstacles associated with trying to attain high top and low bottom temperatures in order to increase efficiency. Classical examples of such devices

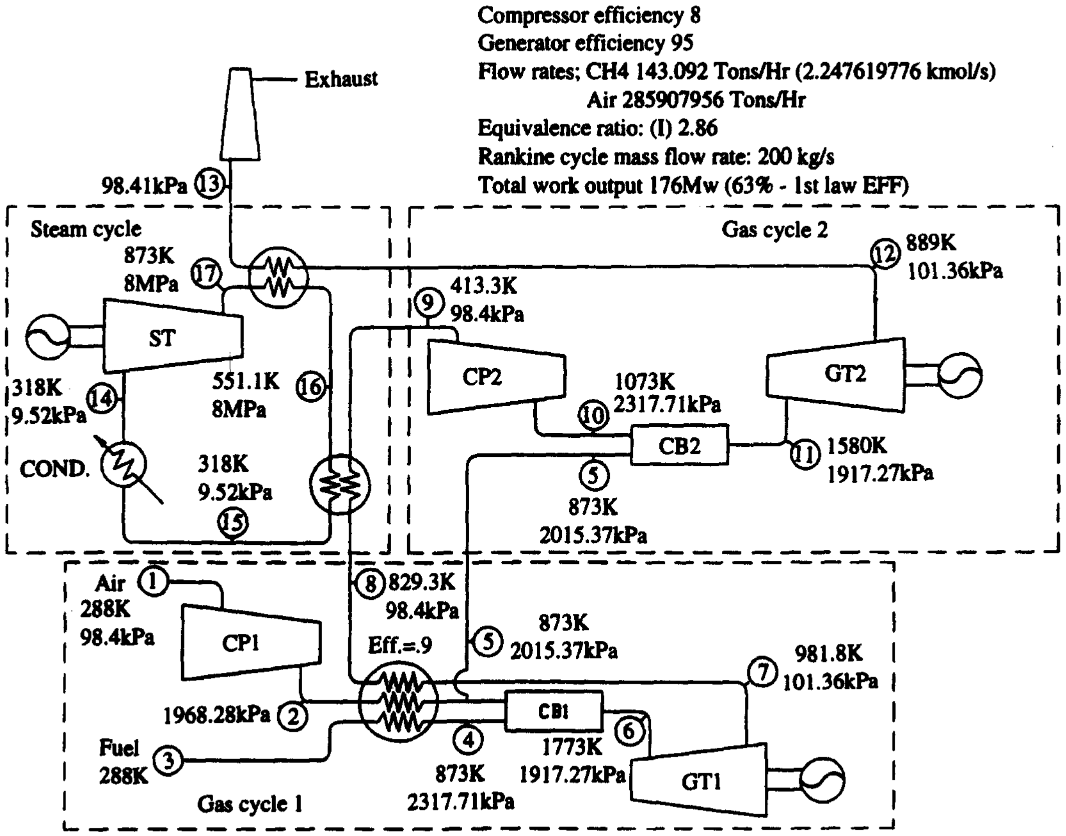

Fig. 5. The RAN "chemical gas turbine" cycle.

are hydro-power plants and water-current or wind turbines. More novel devices are photovoltaic cells, fuel-cells, and battery-like devices which generate energy due to solution concentration differences across a semi-permeable membrane [18]. The encouraging and rapid development of photovoltaic energy conversion was mentioned above. Significant progress is also being made in the development and use of fuel cells [19] and a topping cycle using them [20, 21] is described below.

8.2. *Fuel cells*

Fuel cells convert chemical energy of fuel directly into electricity. In fuel-cell chemical reactions the repositioning of the associated electrons is achieved with greater control than in combustion. In the process, a portion of the electro–chemical energy of electron bonding is extracted electrically rather than being totally dissipated into thermal energy (i.e. into random motion of the reaction components) as in combustion. Thus, there is less associated entropy production than in ordinary combustion, where electron energy is not exploited and the amount of entropy production is left unconstrained.

In as much as the rate of entropy production ($\dot{S}_p$) in a process is

$$\dot{S}_p = \frac{1}{T}\dot{R}\cdot[\text{driving force(s)}] \tag{2}$$

where T is the absolute temperature and $\dot{R}$ is the process rate, to reduce entropy production for a fixed process rate one must either increase the local temperature or reduce the relevant thermodynamic driving force(s). In turn, the rate of useful energy destruction, $\dot{A}_d$, is directly proportional to the entropy production rate

$$\dot{A}_d = T_o\dot{S}_p. \tag{3}$$

By reducing process irreversibilities, device and system efficiencies are improved.

Let us compare the exergetic aspects of ordinary combustion and fuel cell reactions. In ordinary combustion, a fuel is brought in direct contact with oxygen to react and produce oxidation products. The result is a conversion of chemical energy of the fuel to thermal energy of the products [22], in which 20–30% of the fuel exergy is destroyed and approximately 80% of the combustion irreversibility occurs during the internal thermal energy exchange subprocess.

When a fuel is burned in air at the rate $\dot{R}_f$ the driving force for the reaction is the difference between the chemical potentials (μ) of the reactants and products, which is the chemical affinity (λ) of the reaction. The rate of useful power consumption by fuel oxidation is

$$\dot{A}_d = T_o\dot{S}_p = \frac{T_o}{T}\dot{R}_f\lambda = \frac{T_o}{T}\dot{R}_f(\mu_{\text{fuel}} + \mu_{\text{oxygen}} - \mu_{\text{products}}). \tag{4}$$

Fuel cells lower the reaction affinity by first passing ions through an electrolyte. For example, solid oxide fuel cells operate with oxygen ions migrating through a solid electrolyte. By passing oxygen through the solid electrolyte prior to fuel oxidation, such a fuel cell lowers μ_{oxygen}, which, in turn, lowers the power consumption of the oxidation reaction [equation (4)], i.e. the electrochemical potential of oxygen at the anode (where the oxidation occurs) is lower than the value sensed in ordinary combustion, namely the value in the air free stream on the cathode side of the electrolyte.

Upon going through the electrolyte and dropping in potential, the oxygen ions yield electrons at a higher potential (at the anode) than the potential at which they were acquired (at the cathode). The cell thus delivers net power, electrically. Therefore, after passing oxygen through the electrolyte, the fuel oxidation is less violent (less dissipative, less irreversible) inasmuch as the force driving the reaction λ is reduced.

When heat is transferred, the rate of useful power consumption by heat transfer is

$$\dot{A} = -\frac{T_o}{T}\left(\varepsilon\cdot\frac{\nabla T}{T}\right) \tag{5}$$

where ε is the thermal energy flux. By extracting electrical energy during the overall reaction, the energy of the reaction products is reduced. In turn, the temperature gradients between the reaction

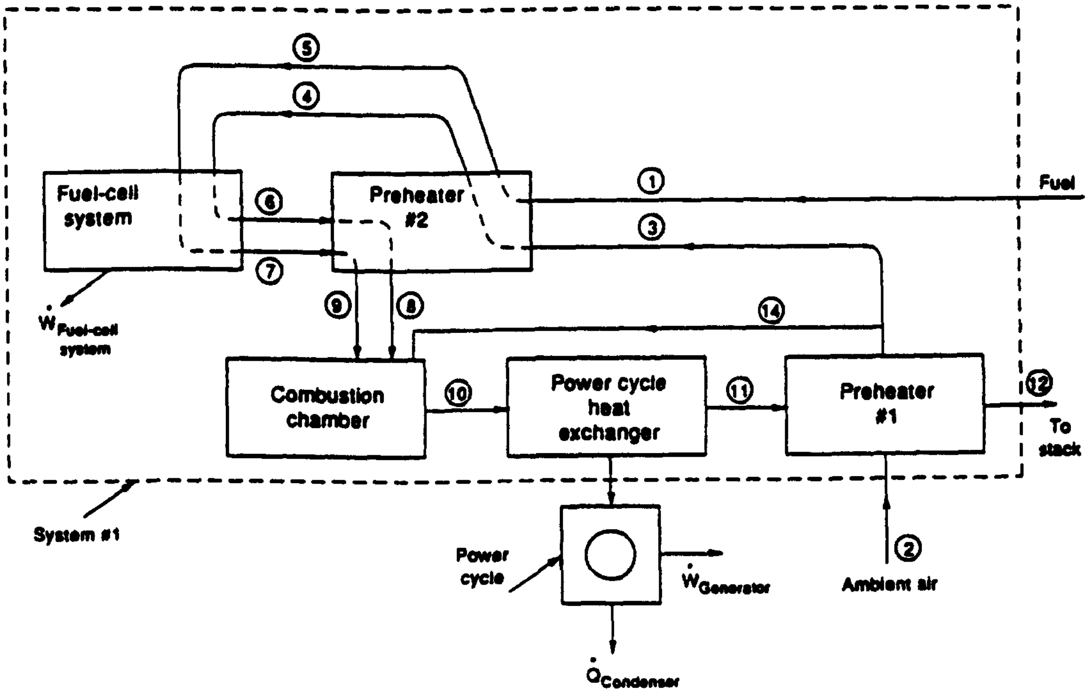

Fig. 6. The plant configuration of a fuel-cell topping power generation system [20].

zone and the neighboring zones is lower than that sensed in ordinary combustion. Thus, relatively less exergy is destroyed during the internal thermal energy exchange [equation (5)].

Although fuel-cell technology has been studied extensively, the best ways to employ fuel-cell units for the generation of electrical power remain to be determined. A number of fuel-cell/power-plant configurations are possible for that purpose. One possible configuration, proposed in [20, 21] and shown in Fig. 6, is the utilization of a fuel cell as a topping unit to an existing or future conventional power plant. In this configuration, hot fuel and oxidant would first be passed through the fuel cell which would thus produce part of the overall electrical output of the plant. After the gases emerge from the fuel cells, still at relatively high temperature, they would be mixed and oxidation would be completed by combustion; the products would be used to generate steam for powering a Rankine cycle plant which produces the remainder of the electrical energy.

An additional benefit of fuel-cell topping systems is the reduction of exergy consumption in subsequent combustion, downstream of the fuel-cell unit in the boiler combustion chamber. This reduction is a consequence of a reduction of the average chemical potentials of oxygen and fuel because they are more dilute after partial oxidation in the fuel cells.

We consider the relationship

$$\mu_i/T = g_i(T,P)/T + \Re \ln \chi_i \tag{6}$$

for ideal gases, where χ_i is the mole fraction of component I and $\Re$ is the universal gas constant. It can be seen that at a given T, as χ_i is reduced for reactants and increased for products, their μ_i/T values are reduced and increased, respectively, with the effect of reducing the value of λ/T. So, if part of the fuel oxidation has been accomplished in fuel cells, thereby decreasing the χ_i of the fuel and oxygen and increasing the χ_i of the products, the value of λ/T at the onset of the subsequent combustion in the boiler is lowered. Since λ/T goes from the initial value to zero as the combustion proceeds, the effect is then to reduce its average magnitude during combustion and, from equation (5), to reduce the exergy destruction. This conclusion is based on the assumption that the temperature of the reactants prior to combustion is essentially the same as in ordinary boiler combustion. It can be seen from the schematic diagram of Fig. 6 that this will be the case, as will be confirmed quantitatively below.

Based on the discussion above, this type of configuration reduces the investment in fuel-cells because they are thereby used only while the chemical driving forces are still high. Instead of continuing the oxidation process with increasingly diluted reactants, which produces concomitantly decreasing power yield, the diluted reactants are fed to the combustor, where they combine more efficiently. It was not implied that this plant configuration is either the most efficient or most economical, but it is a simple example which serves to illustrate the improvement to thermodynamic efficiency when incorporating fuel-cell units into electrical power-generating or cogenerating plants.

This power plant consists of: (1) three heat exchangers (preheater #1, preheater #2 and the power-cycle heat exchanger); (2) a fuel-cell unit; (3) a combustion chamber; and (4) the steam power cycle of an existing 300 MW power plant. Hydrogen is fed to preheater #2 at ambient pressure and temperature, to raise its temperature to the level needed for operating the fuel-cell unit. Ambient air is passed through preheaters #1 and #2 for the same purpose.

Partial oxidation of the fuel takes place within the fuel-cell system. Having delivered an amount of electrical power, the product streams (depleted fuel and air) exit the fuel-cell unit at a higher temperature and, following heat exchange in preheater #2, enter the combustion chamber where fuel oxidation is completed. The combustion product gas then supplies heat first to the power cycle and then to the incoming air. While improvements in solid electrolyte fuel-cells have since been achieved, the fuel-cell performance characteristics in this study are assumed to be those of a Westinghouse Bell-and-Spigot design.

Typical conditions for a case in the analysis are shown in Fig. 7 and the corresponding exergy and energy flow diagram in Fig. 8. The study found that the exergetic efficiency of the fuel-cell unit ranges from 95.9 to 99.9%, increasing with decreasing current. Topping conventional Rankine cycle power plants with fuel cells has been shown (for a range of commercial fuel cells) to increase the exergetic efficiency of the plant by up to 49%, raising that efficiency from the value of 41.5% for the conventional power plant without fuel cells to about 62% for the fuel-cell-topped power plant. This improvement stems from the improved exergetic efficiency of fuel oxidation in these proposed topping power plants, as contrasted with the highly dissipative combustion process in conventional fuel-fired ones. Studies of gas turbine cycles with solid oxide fuel cells were also reported in Ref. [23].

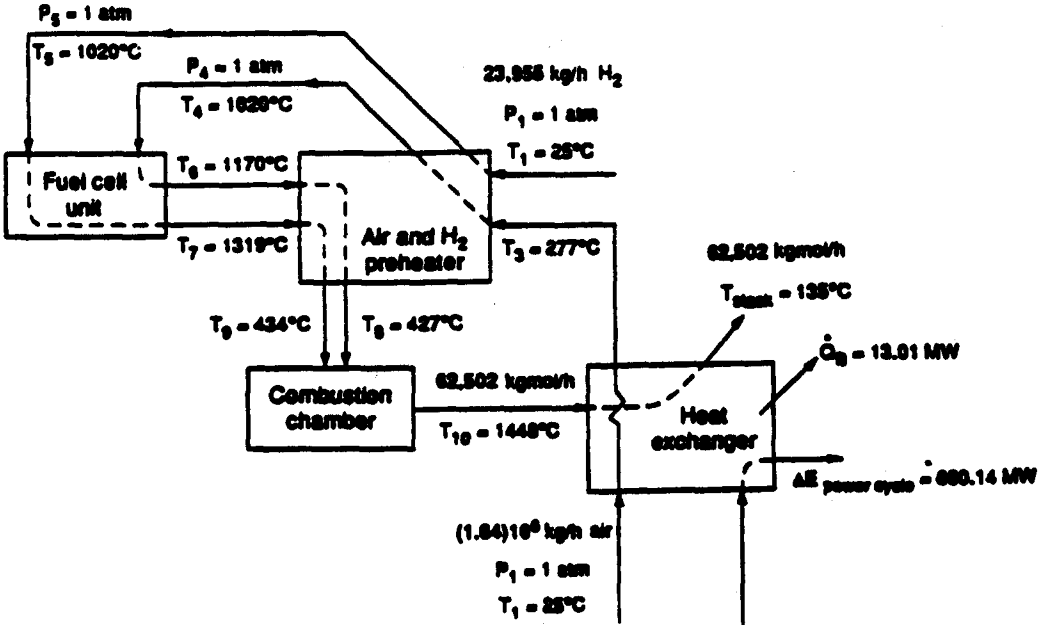

Fig. 7. Analyzed conditions of a fuel-cell topping power generation system [20].

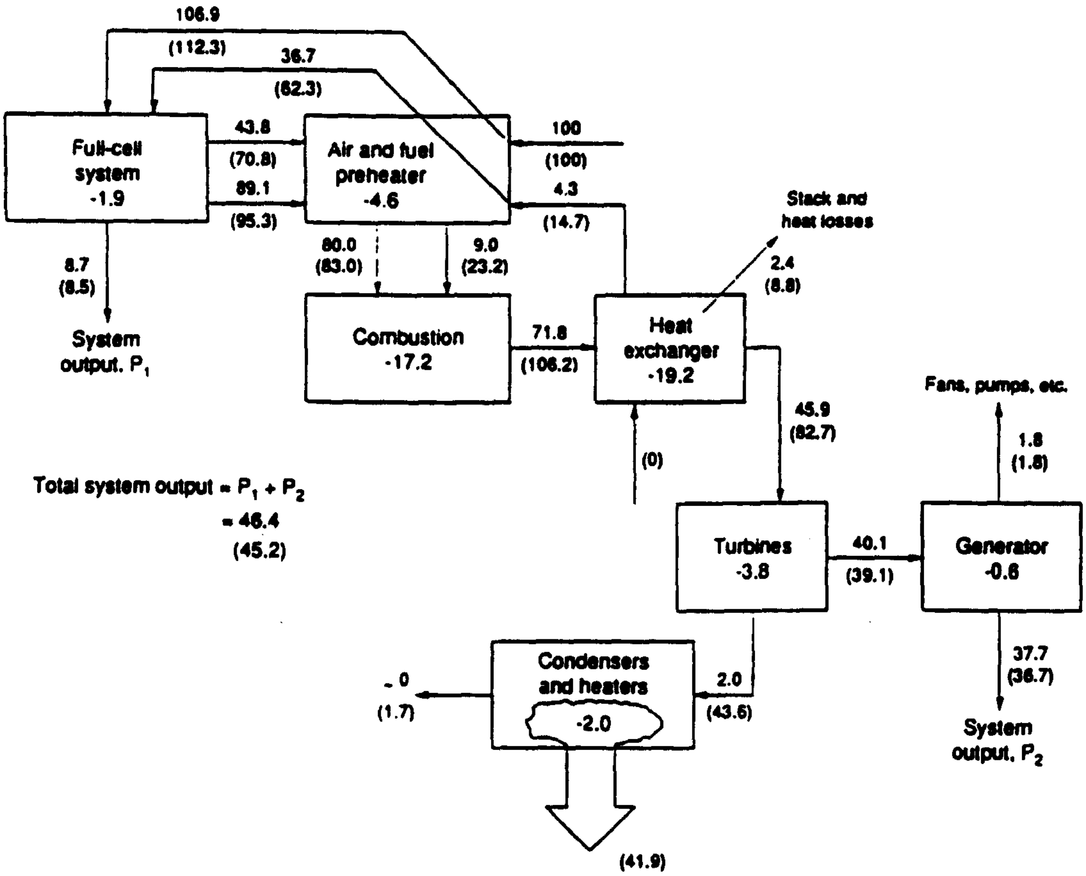

Fig. 8. Exergy and (energy) flow diagrams for a power plant with a fuel-cell topping system [20] (assuming that 100 units of exergy and energy are invested).

8.3. *The nuclear generator?*

Nuclear power plants operate at a thermal efficiency of about 29–35%. Therefore, overall efficiency of electrical power generation may be improved considerably by first understanding and then reducing the irreversibility of nuclear power plant operation.

Past studies of fossil-fuel power stations have revealed that exergy losses associated with boiler operation are highly significant. Conventional combustion is the most inefficient process in fossil-fuel plants, consuming about 20–30% of the useful energy (i.e. of the exergy) of hydrocarbon fuel. Heat transfer from the high-temperature product gases to lower-temperature working fluid destroys another 15% of the fuel's exergy; 5% of the useful energy of fuel is typically expelled with the flue gases. In other words, combustion, heat transfer and flue gas expulsion within/from the steam generator are responsible for over 83% of the irreversibility which occurs during fossil-fuel plant operation.

In comparison with fossil-fuel plants, the fission process replaces combustion to produce the required high-temperature heat for transfer to the working medium of the steam power cycle. In the case of nuclear power stations, there has been little effort directed at the evaluation of exergy destruction within these plants. Siegel [24], employing relations developed by Pruschek [25], performed a second law analysis on a steam-cooled fast breeder reactor plant designed in Germany. He found that the largest exergy loss by far occurs in the reactor itself.

A second law analysis was performed by the author and his co-workers on an operating 1145 MWe BWR nuclear power station to evaluate plant and subsystem irreversibility [10]. The results (Fig. 9) disclose that over 80% of the exergy destroyed during plant operation is a result of the highly-irreversible fission and heat transport processes within the reactor vessel. Plant efficiency and effectiveness are found to be 34.4%, which is well below the 40–45% efficiencies of typical fossil-fuel-fired power generating stations.

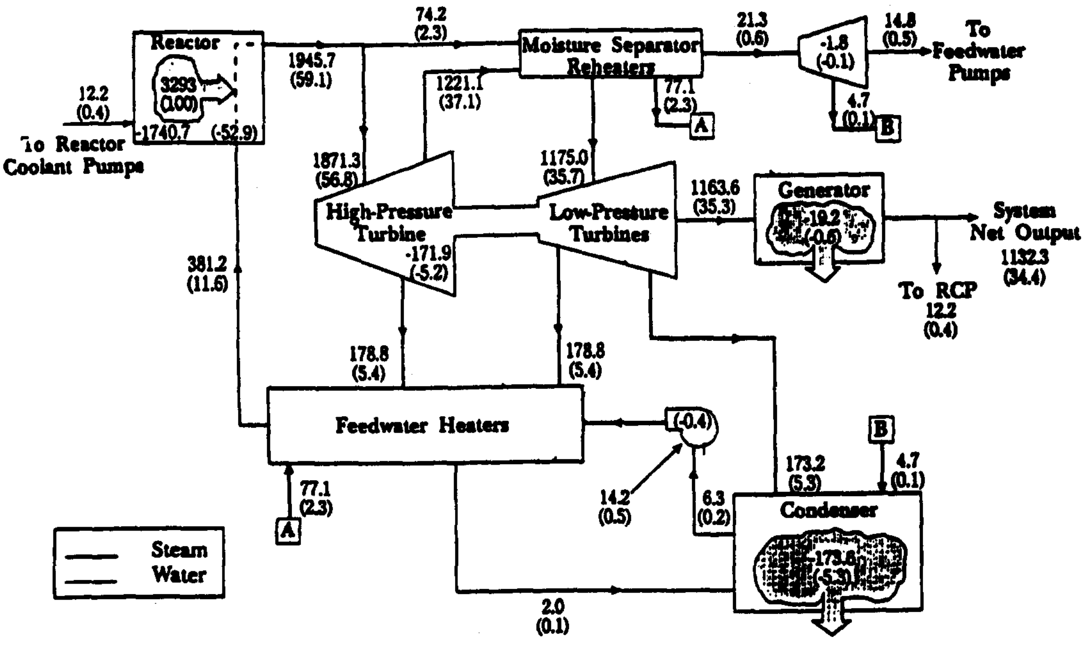

Fig. 9. Exergy flow diagram for the LaSalle County BWR nuclear power station [10] [MW and (% of input exergy)].

Based on these well-known numbers and the results of the exergy analysis, one recommendation is to give attention once again to the integration of fossil-fuel-fired superheat/reheat units located downstream of the reactor vessel. This modified plant configuration would not only improve efficiency by raising the top operating temperature, but is also anticipated to reduce irreversibility associated with heat transfer in the steam generators.

A much more profound conclusion stems from a fundamental examination of the nuclear reaction itself. Most of the energy produced during the breakup of the nucleus in the fission reaction, and in the joining of nuclei in the fusion reaction, is in form of kinetic energy of the produced particles. In a short time and space this valuable mechanical energy, which is pure exergy, is converted into heat as the particles slow down. Even if energy is fully conserved in this slow-down process, much of the original exergy is destroyed, the more so since the top temperatures of the working fluid are severely limited by the safety limits of the fuel rods in the fission reactor and of the fusion system as a whole in a fusion reactor. It is thus obvious that if the original kinetic energy of the fission or fusion products could be used directly to produce electricity, akin to an electro–mechanical nuclear generator, or produce mechanical power directly, this exergy destruction would be eliminated and a much more efficient conversion of the nuclear energy to power may be attained. Similar to past discussions by the authors on the reduction of combustion irreversibility [22], one alternative means to improve the exergy efficiency of nuclear reactions and heat transfer within the reactor would be to devise fission and fusion process which would include generation of useful work during, and as a consequence of, the particle slow-down process. For example, if a system could be devised which would operate as a nuclear generator (or fuel-cell), the nuclear reaction and reactor heat transport irreversibilities would be reduced. Work on a thermodynamic foundation of nuclear reactions is under way [26–28].

9. SOME SUGGESTIONS

While the continuing improvements in conventional power generation technology should not stop, the 21st century should see much more devotion to unconventional frontier approaches to that problem, obviously with proper attention to the accompanying economic and societal issues. The development of new economical materials and devices would allow design of thermal power plants for operation at higher temperatures and efficiencies,but emphasis should be placed on direct energy conversion, i.e. exergy-efficient processes which are neither Carnot-limited nor accompanied by large thermal and species emissions. Among these processes, some of the most appealing at present are direct conversion of solar radiation to electricity, and fuel cells. Devices for these are rapidly declining in price, headed for competitiveness with other power generation schemes and are increasingly used in appropriate commercial applications.

Direct conversion of fission and fusion energy into electrical or mechanical power deserves much attention, especially if the nuclear waste problem is resolved in a definitively satisfactory manner.

The use of space for power generation seems to be inevitable: it provides the best heat sink and relieves the earth from the penalties of power generation. Both the costs of launching payloads into space and those of energy transmission are declining.

In the interim, more efficient production of power from low temperature sources, such as solar and waste heat, co-generation, low-emission combustion systems, exploration of hydrogen as fuel and significantly safer nuclear power production must be pursued.

Since solar energy is an inexhaustible and nonpolluting source which does not alter the global thermal balance, cost reduction in solar power production should be pursued ardently.

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