Solar-Coal Hybrid for Steam Boiler

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Abstract: Solar-coal hybrid is the use of solar and coal energy for producing steam for electricity as opposed to coal alone. The boiler feed-water is pre-heated using solar energy before introduced into the coal boiler, where the steam generating process is finalized for use in the electrical generating turbine. Reviewed is liquid-based direct absorption solar thermal collectors, in which incident sunlight is absorbed directly by the working fluid. Described is the amount of reduction in coal consumption, thus reduction in pollutant.

Keywords: Pollutant, Coal power plant, Steam, DASC, DSG.

1. INTRODUCTION

Coal-fired power plants, which produce almost half of the country's electricity, have significant impacts on coal usage in the United States. One of the four main circuits in any thermal power plant is feed-water & steam-circuit which deals with supplying of steam generated from the boiler to the turbines and to handle the outgoing steam from the turbine by cooling it to form water in the condenser so that it can be reused in the boiler plus making good any losses due to evaporation etc. This article focuses on the feed-water supplied to the boiler. Before water fed into a boiler can be converted into steam, it must be first heated to a temperature corresponding to the pressure within the boiler. If, therefore, the temperature of the water can be increased before it is introduced into a boiler by the utilization of heat from solar source that would otherwise be wasted, there will be a saving in the fuel required, thus coal and pollutants. Phelan *et al.* [1] Trends and Opportunities in Direct-Absorption Solar Thermal Collectors, Boerema *et al.* [2] Liquid sodium versus Hitec as a heat transfer fluid in solar thermal central receiver systems, Taylor *et al.* [3] Applicability of nanofluids in high flux solar collectors, Otanicar *et al.* [4] Nanofluid-based direct absorption solar collector, Kumar and Tien [5] Analysis of Combined Radiation and Convection in a Particulate- Laden Liquid Film.

2. POLLUTANT

A typical 500-megawatt coal power plant produces 3.5 billion kWh per year. That is enough energy for 4 million light bulbs to operate year-round. To produce this amount of electrical energy, the plant burns 1.43 million tons of coal. It also produces pollutant:

Table 1: Coal Power Plant Pollutants

Pollutant	Total for Power Plant	One Light Bulb-Years' Worth
Sulfur Dioxide - Main cause of acid rain	10,000 Tons	5 pounds
Nitrogen Oxides - Causes smog and acid rain	10,200 Tons	5.1 pounds
Carbon Dioxide - Greenhouse gas suspected of causing global warming	3,700,000 Tons	1852 pounds

It also produces smaller amounts of just about every element on the periodic table, including the radioactive ones. In fact, a coal-burning power plant emits more radiation than a (properly functioning) nuclear power plant!

3 FUEL SAVINGS

The saving in the fuel due to the heating of feed-water by means of heat that would otherwise be wasted may be computed from the formula:

$$\text{Fuel saving \%} = 100\,(t - ti) / (H + 32 - ti) \quad (1)$$

t = temperature of feed water after heating

ti = temperature of feed water before heating

H = total heat above 32 degrees per pound of steam at the boiler pressure.

Table **2** has been computed from this formula to show the fuel saving under the conditions assumed with the boiler operating at 180 pounds gauge pressure. Sample values of H for steam at 180 pounds is 1194.4 Btu, as in Table **3**.

Steam at 180 pounds gauge pressure has a temperature of approximately 373.1 °F. If water is fed

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Table 2: Saving in Fuel, in Percent, by Heating Feed-Water Gauge Pressure 180 Pounds

Initial Temp °F	Final Temperature—Degrees Fahrenheit							Initial Temp °F	Final Temperature—Degrees Fahrenheit						
	120	140	160	180	200	250	300		120	140	160	180	200	250	300
32	7.35	9.02	10.69	12.36	14.04	18.20	22.38	95	2.20	3.97	5.73	7.49	9.25	13.66	18.07
35	7.12	8.79	10.46	12.14	13.82	18.00	22.18	100	1.77	3.54	5.31	7.08	8.85	13.28	17.70
40	6.72	8.41	10.09	11.77	13.45	17.65	21.86	110	.89	2.68	4.47	6.25	8.04	12.50	16.97
45	6.33	8.02	9.71	11.40	13.08	17.30	21.52	120	.00	1.80	3.61	5.41	7.21	11.71	16.22
50	5.93	7.63	9.32	11.02	12.72	16.95	21.19	130		.91	2.73	4.55	6.37	10.91	15.46
55	5.53	7.24	8.94	10.64	12.34	16.60	20.86	140		.00	1.84	3.67	5.51	10.09	14.68
60	5.13	6.84	8.55	10.27	11.97	16.24	20.52	150			.93	2.78	4.63	9.26	13.89
65	4.72	6.44	8.16	9.87	11.59	15.88	20.18	160			.00	1.87	3.74	8.41	13.09
70	4.31	6.04	7.77	9.48	11.21	15.52	19.83	170				.94	2.83	7.55	12.27
75	3.90	5.64	7.36	9.09	10.82	15.16	19.48	180				.00	1.91	6.67	11.43
80	3.48	5.22	6.96	8.70	10.44	14.79	19.13	190					.96	5.77	10.58
85	3.06	4.80	6.55	8.30	10.05	14.41	18.78	200					.00	4.86	9.71
90	2.63	4.39	6.14	7.89	9.65	14.04	18.43	210						3.92	8.82

Table 3: Properties of Saturated Steam Reproduced by Permission from Marks and Davis "Steam Tables and Diagrams" (Copyright, 1909, by Longmans, Green & Co.)

Pressure, Pounds Absolute	Temperature °F.	Specific Volume Cu. Ft. per Pound	Heat of the Liquid, Btu	Latent Heat of Evap., Btu	Total Heat of Steam, Btu
180	373.1	2.533	345.6	850.8	1196.4

to the boiler at 60 °F, each pound must have 345.6 Btu added to it to increase its temperature to 373.1 degrees before the water can be converted into steam. As it requires 1196.4 Btu to raise one pound of water from 60 to 373.1 degrees and to convert it into steam at 180 pounds gauge pressure, the 313.1 degrees required simply to raise the temperature of the water from 60 to 373.1 degrees will be 100 (373.1 – 60) / (1196.4 + 32 – 60) = 27% fuels saving of the total. If, therefore, the temperature of the water can be increased from 60 to 373.1 degrees before it is introduced into a boiler by the utilization of heat from solar source that would otherwise be wasted, there will be a saving in the fuel required of 27%, thus coal and pollutants, and there will be a net saving, provided the cost of maintaining and operating the apparatus for securing this saving is less than the value of the heat thus saved.

Solar generated hot water could reduce the amount of coal required by steam generating coal boilers by 27% if the boiler feed water is pre-heated by liquid-based direct absorption collector. Depending on the type of collector used, and the level of solar radiation available, fluid working temperatures can be achieved ranging from 120 °F to 750 °F or more. Dish concentrators can achieve even higher levels of concentration, and correspondingly higher temperatures. Direct-absorption solar collectors are inherently attractive because absorbing sunlight directly into the working fluid eliminates the intermediate heat transfer step posed by a solid absorber, thus generally improves the receiver efficiency. From a practical point of view, a nanofluid-based receiver may be particularly attractive in solar "power tower" configurations.

4. TYPES OF DIRECT ABSORPTION SOLAR COLLECTORS (DASC)

Direct absorption solar collectors are categorized based on their operational temperature - low (<480 °F), medium (480-930 °F) and high (>930 °F) temperature direct-absorption solar collectors.

Medium temperature (480-930 °F) direct absorption solar collectors are of interest for our purpose in this article. A unique requirement for direct-absorber fluids is that they must be able to withstand UV light - *i.e.* destructive, high energy photons. This is not a requirement for the working fluids in conventional solar collectors since they are not directly exposed to incoming solar energy.

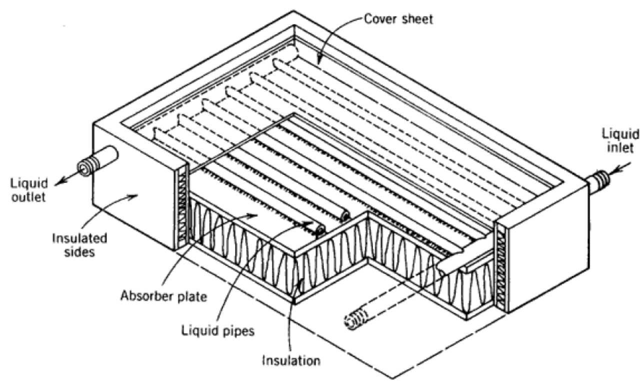

Figure 1: A typical liquid flat-plate collector. From Powerfromthesun.net.

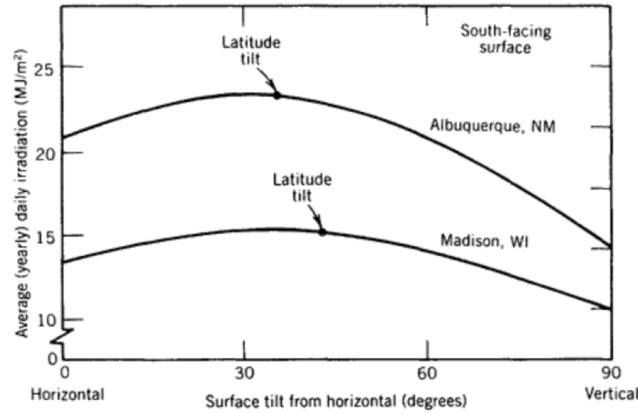

Figure 2: Total (global) irradiation on a south-facing tilted surface. Average ground reflectance was assumed to be 0.20. From Powerfromthesun.net.

5. MEDIUM-TEMPERATURE SYSTEMS

At medium temperatures (480-930 °F), candidate liquids for direct absorption at medium temperatures are liquid metals and molten salts. Liquid metals, such as mercury and sodium, have been proposed and even used in solar systems, but not as direct absorbers. Sodium is liquid from 208 °F to 1603 °F, has a nearly stable specific heat (1.4-1.2 kJ/kg.K) and a high thermal conductivity (90-60 W/m.k) over this range. In the medium temperature range there are several research articles which have studied molten salts as the base fluid for direct absorption. Nitrate salts (*i.e.* a 40- 60 eutectic mixture of KNO_3-$NaNO_3$) are

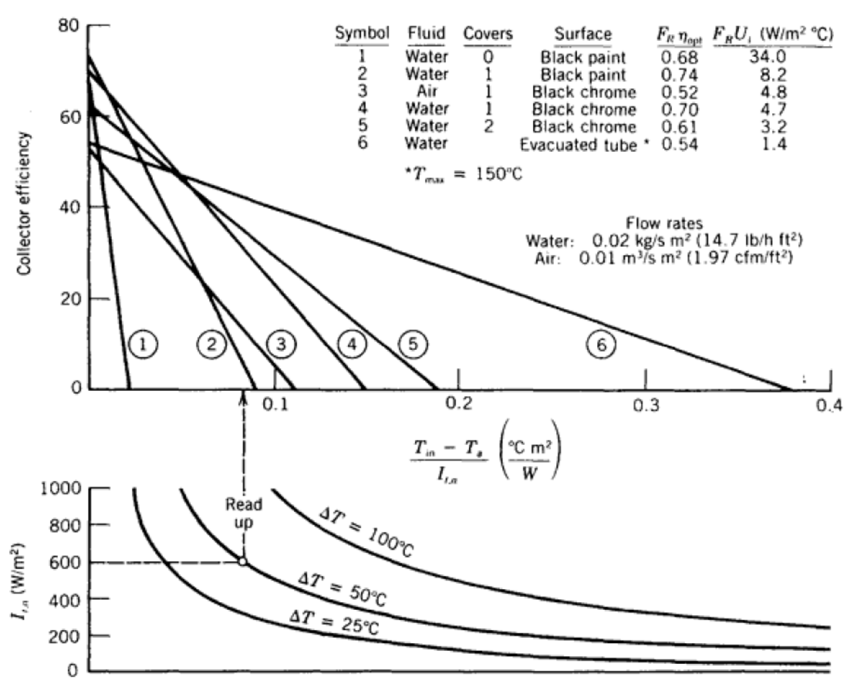

Figure 3: Performance of typical commercial flat-plate solar collectors. From Powerfromthesun.net.

particularly well suited to medium temperature applications because they are of relatively low cost (< \$0.5/kg). There are many other potential salt mixtures, but nitrate salts are the most well-developed because they have been frequently used in solar systems.

6. RELEVANT EQUATIONS

On the most basic level, any problem relating to direct-absorption solar collectors can be represented by two key equations: the energy equation and the radiative transport equation. The energy equation can be written in various forms depending upon the different geometry and flow conditions considered. Here a general three-dimensional version is used where the flow is confined to the z-direction with both heat and radiative transport in the x-y-z directions (but a variety of different approaches can be found elsewhere):

$$P\, C_p\, V\, \partial T/\partial z = k\, (\, \partial^2 T(x,y,z) / \partial x^2 + \partial^2 T(x,y,z) / \partial y^2\,) - \partial q_{r,x}/\partial x - \partial q_{r,y}/\partial y - \partial q_{r,z}/\partial z \qquad (2)$$

where,

ρ = density,

C_p = specific heat,

V = velocity,

T = temperature,

k = thermal conductivity, and

qr = radiative flux.

The first term on the left-hand side represents convection-dominated thermal transport in the z direction, while the first term on the right-hand side is the conduction-dominated thermal transport mechanism only in the x and y directions. The last three terms are the divergence in radiative flux terms which link the energy equation to the radiative transport equation - *i.e*. the other key equation in a direct-absorption simulation. The radiative transport equation can be given by:

$$dI'_\lambda/dS = - \sigma_{a,\lambda}\, I'_\lambda(S) + \sigma_{a,\lambda}\, I_{b,\lambda}(S) - \sigma_{s,\lambda}\, I'_\lambda(S) = \sigma_{s,\lambda}/4\pi \int^{4\pi} I'_\lambda(S,\omega)\, \Phi(\lambda,\omega,\omega_i)\, d\omega_i \qquad (3)$$

where,

I'_λ (S) = the radiative intensity in an arbitrary direction S,

$\sigma_{a,\lambda}$ = the absorption coefficient,

$I_{b,\lambda}$(S) = the blackbody radiative intensity,

$\sigma_{s,\lambda}$ = the scattering coefficient,

Φ = the scattering phase function and

ω = the solid angle.

The equation presents the change in radiation intensity due to absorption, emission, out-scattering and in-scattering. It should be noted that no closed-form solution exists for this equation except for simple geometries resulting in complex solution procedures. The energy equation utilizes the divergence in radiative flux to determine volumetric heating within the system. This is done by considering the difference between the radiative flux in the positive and negative directions for a given volume in each direction. While such equations govern transport within the system, key parameters in Eq. (3) still need to be determined, namely the scattering and absorption coefficients. These coefficients are extremely important to the design of the device and are highly size, shape and scattering mode dependent. The assumptions taken for these often result in equations of differing difficulty and solution technique.

7. SOLUTION APPROACHES

Solution approaches for direct-absorption systems are often based on combining the two key equations. For radiative transport, typical approaches are based upon the Monte Carlo technique and the Differential-Discrete-Ordinate Method for systems where multiple directions and angles need to be considered. Considerably simpler approaches are available when in-scattering is neglected, and the geometry is reduced such that radiative transport occurs only in one dimension. From a numerical perspective, the solution to the radiative transport equation presents a much more challenging solution procedure. The solution of the energy equation can be solved with more conventional techniques, such as finite differences.

8. DIRECT-STEAM GENERATION (DSG)

Worth mentioning, although not in the scope of this article is the direct steam generation which could further eliminate coal in the solar-coal hybrid. Direct steam generation is one possible (yet underdeveloped) application of direct-absorption solar collectors. Many researchers have reported on 'direct steam generation', but this usually indicates that solar energy is used to boil water via a solid surface directly inside the receiver. This requires an intermediate working fluid which flows between the receiver and the steam generator. The concept proposed here, however, is to expose an aqueous particle suspension directly to light. If the irradiance is high enough vapor can form in the volume of the fluid. Initial work by Taylor *et al*. has shown that since heat losses can be minimized (vs. surface-based collection), it is possible to enhance vapor generation and reduce irradiance necessary for boiling incipience. If nanoparticle suspensions are used as the working fluid, this can potentially take advantage of enhanced boiling heat transfer properties (namely enhanced critical heat flux).

CONCLUSIONS

Solar-coal hybrid could be another form of clean coal considering the 27% savings in the amount of coal used in the electricity producing coal boiler plants, thus 27% less emission of pollutants. The potential benefits provided by direct-absorption solar collectors enable thermal commercial opportunities. If the enhanced performance promised by direct absorption can be realized, it will have a very large impact in the thermal applications in boiler feed water temperature. Direct-absorption solar collectors show great potential for efficient conversion of sunlight to thermal energy. The thermal energy can be used for increasing boiler feed water, therefore reducing the amount of coal required to achieve the boiler feed-water conversion to steam. From a commercial point of view, it may be acknowledged that although direct absorption collectors (DAC) have been known for decades there is still limited commercial availability in DAC for low/medium temperature applications.

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