Technical News Features

Design of a 5500 lb/hr Solar Steam Plant

D.J. ALLEN, A.C. GANGADHARAN and **S. KUMAR**, Foster Wheeler Solar Development Corporation, 12 Peach Tree Hill Road, Livingston, NJ 07039

ABSTRACT

Solar thermal systems capable of providing process heat to the industries that make up the Food and Kindred Products Group are now commercially available. Whether or not they will be adopted by these industries will depend not only upon further reductions in capital costs, but also upon the costs and availability of alternative fossil fuels, the operating and maintenance costs of solar thermal systems, and tax incentives.

INTRODUCTION

Research and development work in solar energy technologies gained a new momentum in 1973. The cause célèbre was the oil embargo by the OPEC nations and the resultant economic strains felt throughout the world. In the years that followed, the industrialized countries such as the United States, Canada, France, Western Germany and Japan increased their solar R & D budgets manyfold. For example, in the United States alone, the Federal solar R & D budget rose from $15 million in 1974 to $600 million in 1981. A survey conducted by the United Nations reported that during the post-oil-crisis period, 57 developing countries undertook some kind of nonconventional energy resources assessment program. Since 1973, the UN and other world agencies have funded 158 programs with an aggregate funding of $148 million. Bilateral assistance in nonconventional energy has also increased considerably during the same period. Brazil, Canada, Egypt, France, West Germany, India, Italy, The Netherlands, Norway, Saudi Arabia, the United Kingdom and the USSR participated in such projects. The general conclusion to be drawn from these and other data is that there is a worldwide upsurge of activities in solar and other renewable energy technologies and that the activities will have a significant impact on the energy market sector in the years ahead.

In the United States, solar energy research and development has culminated in a determined attempt to commercialize photovoltaic and solar thermal systems. In this paper we will describe one such system on which we in Foster Wheeler have been working: a parabolic trough solar thermal system.

COLLECTOR FUNDAMENTALS

Concentrating collectors utilize reflectors or refractors to increase the intensity of solar radiation on the absorber. Distributed concentrating collectors can be classified as one-axis and two-axis tracking systems. Although the theoretical concentration limits for one-axis tracking systems can reach 215, in reality single-axis tracking systems on the market have concentration ratios from 10 to 60. As a result, one-axis tracking collectors are capable of producing temperatures up to ca. 300 C (572 F). Solar collectors for energy to be delivered above 300 C (572 F) must be able to track the sun about two axes. The performance of one-axis trackers (parabolic trough) is generally evaluated in one of three specific configurations: east-west, north-south, and polar.

In an east-west layout, the absorber tube is oriented east-west and tracks the sun as it moves in a north-south direction. In a north-south configuration, the absorber tube is oriented north-south and tracks the sun as it moves from east to west each day. In a polar mount, the absorber tube is oriented north-south and tilted up from the horizontal by the latitude angle.

The polar-mounted collectors generate the highest amount of energy annually, primarily because losses of incident energy are kept to a minimum. The north-south horizontal trough produces less annual energy than the polar-mounted collector, and the east-west horizontal orientation produces the least annual energy of the three configurations. Generally, the east-west trough produces more uniform output annually than the north-south trough orientation, while capital costs and design difficulties preclude the use of polar-mounted collectors.

INDUSTRIAL THERMAL ENERGY DEMAND

The demand for process heat is enormous – ca. 20% of total US energy consumption. Of this demand, some 80% is now provided by premium fuels (oil and gas). This process heat is used in many applications over a very wide temperature range; 25, 50 and 70% of process heat is required at temperatures less than or equal to 200, 500 and 1000 F (93, 260 and 538 C), respectively. Throughout this range of temperatures, there are solar thermal systems that can operate effectively.

Some of the considerations for the selection and matching of solar thermal systems to applications are:

– the temperature level of the process heat and the temperature tolerance imposed on the required process heat;
– thermal energy demand as a function of time;
– the response characteristics of the backup energy systems to fluctuating loads imposed by variations in available solar energy; and
– the location of the project and the local climate.

Obviously, the best application for a solar thermal system is one which can accommodate all the solar energy that can be collected in a location where the insolation is high.

One group of industries particularly suited for the application of solar energy is the Food and Kindred Products Group (US Department of Commerce, Standard Industrial Group 20). This group of industries requires thermal energies at temperatures well below 400 F (204 C). In 1974 they consumed 319×10^{12} Btu (3.36×10^{17} J). Of this, ca. 11% was consumed by soybean oil mills, animals and marine fats, and shortening and cooking-oil industries in a temperature range between 160 and 350 F (71 and 177 C). In this temperature range, concentrating collectors can find many applications should economic incentives be available.

PARABOLIC TROUGH COLLECTOR SYSTEMS

In the past several years, much effort has gone into the development of solar thermal systems utilizing parabolic trough collectors. This work has included the design and demonstration of both components and complete systems. In the United States, government-funded development has culminated in the Modular Industrial Solar Retrofit (MISR) System Development Program. In this program, detailed designs have been prepared for modular systems, and work is now under way to test them.

The intent of the MISR program is to commercialize modular, dispersed, solar thermal systems, incorporating the lessons learned in previous programs. These modular systems are designed to use ~25,000 ft^2 (2300 m^2) of collectors to generate up to 550 lb/hr (2470 kg/hr) of 250 $lb/in.^2g$ (1.72 MPa) saturated steam. We in Foster Wheeler have participated in the MISR program and are now offering a modular system that uses pressurized water as a heat-transfer fluid. Other manufacturers offer similar systems using organic heat-transfer fluids.

Design

The solar thermal system designed by Foster Wheeler is simple, partially self-regulating, and automatically controlled (Fig. 1). In it, pressurized water is circulated from an accumulator, through the solar collector field, to the steam generator and is then returned to the accumulator. Under design conditions the water, at ~800 $lb/in.^2g$ (5.51 MPa), is heated from 420 to 500 F (215 to 260 C) as it circulates through the collector field. Boiling is prevented by maintaining a partial pressure of nitrogen within the accumulator so that the vapor pressure of water is always exceeded within the pressurized-water heat-transfer loop. Pressure can be maintained without continuously supplying nitrogen by relying upon the thermal expansion of water into the accumulator and the increase in temperature in the accumulator to ensure a sufficiently high partial pressure of nitrogen.

Water as a heat-transfer fluid conveying thermal energy from the solar collectors to the steam generator offers several advantages: it is inexpensive, environmentally innocuous, cannot degrade, and has excellent heat-transfer properties. In contrast, organic heat-transfer fluids are flammable, degrade, and are less effective as heat-transfer agents. Consequently, if organic heat-transfer fluids are used, additional capital costs are incurred for fire protection and additional heat-transfer area for steam generation. Furthermore, operating costs increase because these organic fluids degrade, must be replaced periodically, and must also be circulated at higher rates than would be required with water.

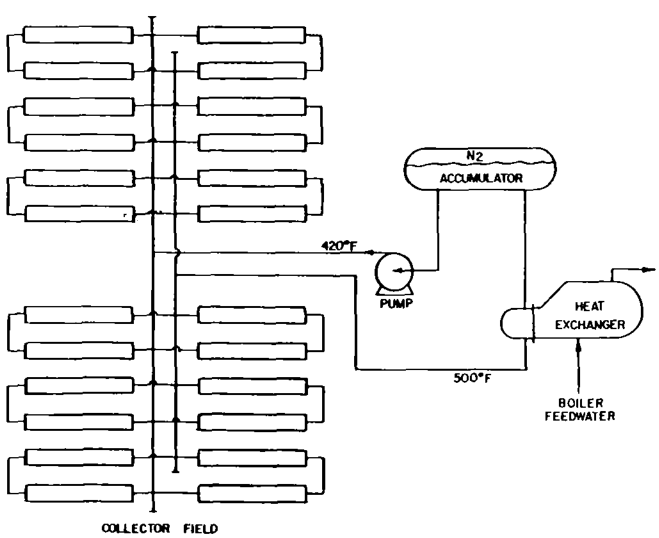

FIG. 1. Schematic of solar thermal system.

The disadvantages of water as a heat-transfer fluid are, of course, its high vapor pressure under the design operating conditions for this system and its potential for freezing. Although both these concerns can be dealt with, operation of such a system may not be economical in locations that experience prolonged, cold winter weather.

The parabolic trough collectors have a silvered glass parabolic surface that reflects and concentrates the sunlight upon a receiver tube through which pressurized water is circulated. Silvered glass offers the best performance of all mirror surfaces – its specular reflectance is high and it is easy to clean and maintain. The receiver tube, surrounded by an annular glass tube, is coated with black chrome for fairly high surface absorptivity, very low emissivity, and thus enhanced collection efficiency. A vacuum is maintained in the space between the receiver the glass tubes to minimize conductive and convective heat losses from the receiver tube.

In our solar thermal system, the collectors are 120 ft (36 m) long with an aperature (mirror rim-to-rim distance) of 10 ft (3.05 m). The dimensions and layout represent the results of a series of trade-off studies of such factors as end losses; wind loads and the ability of the mirrors to focus accurately; and the cost of manifolds, collector controls and pumping.

With the parabolic trough collectors, both the receiver tube and collector mirror rotate to keep the sun's reflected image focused upon the receiver tube. Accordingly, the connection between the receiver tubes and the manifolds conveying the water to and from the collectors must also rotate. To accomplish this, we use a flexible hose that also accommodates thermal expansion in the receiver tubes and manifolds.

The remainder of the system is simple, consisting of a pressurized-water circulation pump, a steam generator, an accumulator, an instrument air compressor, motor control gear and an instrument panel. To enhance the performance and reliability of the system, we have made no attempt to control the temperature of the water as it emerges from the collector field. Rather, the pressurized water is circulated at a constant rate; therefore, should insolation (intensity of sunlight) decline, then so also do the water exit temperature and heat losses. By this means, solar energy is collected as efficiently as possible without the possibility of water temperature and pressure excursions as a result of inadequate or failed temperature controls.

Earlier, we mentioned that this solar thermal system is modular. We have achieved this modularity in our detailed design and in our fabrication and installation plans by minimizing both the site-specific design work required and the amount of field work. In particular, the pump, vessels, instrument air compressor, control panel and instrumentation are prefabricated, shop-mounted upon a skid, and tested before shipping. Similarly, the pipes and rotary connections are prefabricated, piece marked and tested prior to shipping. By this means, site work is limited to site preparation, the pouring of foundations, the erection of the collectors, the bolting together of prefabricated pipes, the insulation of pipes off the skid, the hooking up of power supplies, the laying of control and power cables between the collector field and the skid and the connection of the solar thermal system to the plant. Field welding is limited to the joining of 20 ft (6.1 m) sections of receiver tube, the welding of adjustment pieces joining the flexible hoses to the receiver tubes, and the welding of pipe supports.

Following installation and start-up of the solar thermal system, unattended operation should be possible. Routine maintenance of such a facility is expected to be limited to the lubrication of the collector drives and the cleaning of

TABLE I

MISR System Performance[a]

Location	Collector orientation	Annual steam output kg × 10^6 (lb × 10^6)	Annual steam output/ unit collector area kg/m² (lb/ft²)	Annual thermal output/ unit collector area GJ/m²
Boston	N-S	1.836 (4.048)	708 (145)	1.71
	E-W	1.184 (2.612)	459 (94)	1.10
Charleston	N-S	2.907 (6.410)	1123 (230)	2.70
	E-W	1.824 (4.022)	703 (144)	1.69
Fort Worth	N-S	3.354 (7.395)	1299 (266)	3.11
	E-W	2.124 (4.683)	820 (168)	1.97
Fresno	N-S	3.903 (8.605)	1508 (309)	3.62
	E-W	2.307 (5.087)	894 (183)	2.14
Albuquerque	N-S	4.941 (10.890)	1909 (391)	4.58
	E-W	3.270 (7.210)	1265 (259)	3.03

[a]Collector area: 2587 m² (27,840 ft²). Feedwater temperature: 93 C (200 F). Saturated steam temperature: 208 C (406 F).

the mirrors where rain is inadequate for this purpose in addition to normal maintenance on the pump, instrument air compressor and instrumentation.

Operation

The successful use of solar thermal energy by industry will likely require the selection of sites with high insolation and low winds and of applications that allow full use to be made of all solar thermal energy collected.

The modular solar thermal system we have designed is capable of generating up to 5500 lb/hr (2490 kg/hr) saturated steam at 250 lb/in.^{2}g (1.72 MPa) under conditions of maximum insolation within North America, but the actual energy delivered will vary according to the insolation and thus to the location (Table I). This variation will be reflected in the delivered cost of solar thermal energy.

Costs

The attractiveness of solar thermal systems to industry lies in their ability to reduce the consumption of oil and gas by substituting solar thermal energy in their place. Their potential will, of course, be determined by their ability to do this at a reasonable cost. This cost will be determined by the capital cost of the solar thermal system, by its operating and maintenance costs, and by tax policies and incentives afforded to the user of solar energy.

Assuming that mass production of these modular solar thermal systems can be achieved, we believe a capital cost of $1.2 × 10^6 (US) for such a system can be attained. Making the assumptions presented in Table II, we can calculate the delivered cost of solar thermal energy as 250 lb/in.^{2} g (1.72 MPa) saturated steam in various locations (Table III). Until the prices of oil and gas rise further, however, the economics of parabolic trough solar thermal systems remain marginal.

Larger Solar Thermal Systems

Thus far we have concerned ourselves with modular solar thermal systems that utilize ~25,000 ft^2 (2300 m^2) of collectors to generate up to 5500 lb/hr (2490 kg/hr) saturated steam at 250 lb/in.^{2}g (1.72 MPa). The size of these modules was selected to ensure that the noncollector equipment cost/unit area of collector field is low, but at the same time a system is offered that is appropriate to as many users as possible. However, many users will be able to accommodate more steam than a single module is able to produce. In these circumstances, multiple modules can be installed, allowing clients to make use of existing, proven designs. Furthermore, by using multiple modules, the average distance between the collector field and equipment skid can be kept as small as possible, minimizing overnight heat losses and the volume of water to be accommodated in the accumulator. (Note: No attempt is made to recover the sensible heat left in the pipes and receiver tubes at the end of the day.) Although further economies of scale can be achieved by using larger vessels and pumps – provided these too can be shipped – our preliminary estimates indicate that little will be gained by not making full use of the existing modular design in building larger solar thermal systems.

TABLE II

Assumptions in Economic Analysis

Item	Assumption
Costs	In May 1982 dollars
Income tax	46% effective rate
Local taxes	Not charged
Investment tax credit	25%
Funding	50% equity funding, 50% debt
Insurance costs	0.1%/yr
Salvage value	Zero
Depreciation method	Double declining balance
Depreciation period	5 years
Project life	20 years
Investment schedule	Investment made in May 1982
Annual operations and maintenance costs[a]:	
Electricity	4 ¢/kW hr
Operating manpower	$5,000/yr
Maintenance:	
Collectors	3%/yr of capital cost
Remainder of system	2%/yr of capital cost
Inflation rate	8%/yr
Installation date	May 1982
Discounted cash flow rate of return on equity	15%/yr
Interest rate on debt	14%/yr

[a]No charges are made for chemicals and water.

TABLE III

Delivered Cost of Solar Thermal Energy at Various Locations

Location	Delivered cost of solar thermal energy \$/GJ (\$/10^6 Btu)[a]
Boston	29.60 (31.21)
Charleston	18.70 (19.71)
Fort Worth	16.20 (17.08)
Fresno	13.93 (14.68)
Albuquerque	11.00 (11.60)

[a]Delivered levelized cost in constant 1982 US dollars.

[Received November 10, 1982]