Design of a Solar Low Temperature Steam Generation System

Soteris Kalogirou
Mechanical Engineering Department, Higher Technical Institute, P.O. Box 423,
Nicosia, Cyprus, Tel: +357-2-306199, Fax: +357-2-494953

ABSTRACT

The three methods employed for solar steam generation are analyzed with respect to their advantages, operating problems, operational stability, and cost. From this analysis the steam-flash system is selected because it has advantages with respect to other systems due to the superiority of the water as a heat transfer fluid, the relatively low capital cost, and the avoidance of any flow stability problems. The design of the flash vessel, which is the main part of the system, is then presented. The flash vessel size and inventory determines how much energy is invested in heating-up the system in the morning therefore optimisation of the system is necessary. Finally design graphs for the optimum flash vessel design are given. These graphs can be used for a quick design of the flash vessel inventory, diameter and height within the range considered here, up to a collector aperture area of about 2200 m^2.

1. INTRODUCTION

Parabolic trough collectors are frequently employed for solar steam generation because temperatures of about 300 °C can be obtained without any serious degradation in the collector efficiency. A typical application of this type of system is the Southern California power plants known as Solar Electric Generating Systems (SEGS) which have a total installed capacity to date of 354 MWe (Kearney and Price, 1992).

Low temperature steam is defined as steam with temperature up to 120 °C. Such temperature steam can be used in industrial applications, sterilisation, and for powering desalination evaporators.

Three methods have been employed to generate steam using parabolic trough collectors: (i) The steam-flash concept, in which pressurised water is heated in the collector and then flashed to steam in a separate vessel. (ii) The direct or in-situ concept, in which two phase flow is allowed in the collector receiver so that steam is generated directly. (iii) The unfired-boiler concept, in which a heat-transfer fluid is circulated through the collector and steam is generated via heat-exchange in an unfired boiler. All these systems have certain advantages and disadvantages and these will be analyzed here to select the best system. This will be followed by the flash vessel design and optimisation.

2. SELECTION OF THE STEAM GENERATION METHOD

A diagram of a steam-flash system is shown in Fig. 1. Water, pressurised to prevent boiling, is circulated through the collector and then flashed across a throttling valve into a flash vessel. Treated feedwater input maintains the level in the flash vessel and the subcooled liquid is recirculated through the collector. The in-situ boiling concept, shown in Fig. 2, uses a similar system configuration without a flash valve. Subcooled water is heated to boiling and steam forms directly in the receiver tube. Capital costs associated with a direct-steam and a flash-steam system would be approximately the same (Hurtado and Kast, 1984).

Although both systems use water, a superior heat transport fluid, the in-situ boiling system is more advantageous. The flash system uses a sensible heat change in the working fluid, which makes the temperature differential across the collector relatively high. The rapid increase in water vapour pressure with temperature requires corresponding increase in system operating pressure to prevent boiling. Increased operating temperatures reduce the thermal efficiency of the solar collector. Increased pressures within the system require a more robust design of collector components, such as receivers and piping. The differential pressure over the delivered steam pressure required to prevent boiling is supplied by the circulation pump and is irreversibly dissipated across the flash valve. When boiling occurs in the collectors, as in an in-situ boiler, the system pressure drop and consequently, electrical power consumption is greatly reduced. In addition, the latent heat-transfer process minimises the temperature rise across the solar collector. Disadvantages of in-situ boiling are the possibility of a number of stability problems (Peterson and Keneth, 1982) and the fact that even with a very good feedwater treatment system, scaling in the receiver is unavoidable. In multiple row collector arrays, the occurrence of flow instabilities could result in loss of flow in the affected row. This in turn could result in tube dryout with consequent damage of the receiver selective coating. No significant instabilities were reported by Hurtado and Kast (1984) when experimentally testing a single row 120 ft system.

A diagram of an unfired boiler system is shown in Fig. 3. In this system, the heat-transfer fluid should be nonfreezing and noncorrosive, system pressures are low and control is straightforward. These factors largely overcome the disadvantages of water systems, and are the main reasons for the predominant use of heat-transfer oil systems in current industrial steam-generating solar systems.

The major disadvantage of the system result from the characteristics of the heat-transfer fluid. These fluids are hard to contain, and most heat-transfer fluids are flammable. Decomposition, when the fluids are exposed to air, can greatly reduce ignition-point temperatures, and leaks into certain types of insulation can cause combustion at temperatures that are considerably lower than measured self-ignition temperatures. Heat-transfer fluids are also relatively expensive and present a potential pollution problem that makes them unsuitable for food industry applications (Murphy and Keneth, 1982). Heat-transfer fluids have much poorer heat-transfer characteristics than water. They are more viscous at ambient temperatures, are less dense, and have lower specific heats and thermal conductivities than water. These characteristics mean that higher flow rates, higher collector differential temperatures, and greater pumping power are required to obtain the equivalent quantity of energy transport when compared to a system using water. In addition, heat-transfer coefficients are lower, so there is a larger temperature differential between the receiver tube and the collector fluid. Higher temperatures are also necessary to achieve cost effective heat exchange. These effects result in reduced collector efficiency.

From the above discussion it is obvious that the water-based systems are more simple and safer. It should be noted that a relatively low pressure of 2 bars is required for the low temperature application considered here (up to 120 °C) to keep water in liquid form, therefore the pump power requirement is small. For a given collector area and by considering a maximum value of solar radiation of 1000 W/m^2 and a design water flow rate equal to 0.012 kg/s/m^2, the temperature differential across the collector would be 20 °C. From this analysis it is obvious that the main disadvantages of the steam-flash against the in-situ system are reduced. As their costs are similar the steam-flash system is selected.

3. FLASH VESSEL DESIGN

In order to separate steam at lower pressure, a flash vessel is used. This is the main component of the steam-flash system. It is a vertical vessel as shown in Fig. 4, with the inlet for the water located at its side. The standard design of flash vessels requires that the diameter of the vessel is chosen so that the steam flows towards the top outlet connection at no more than about 3 m/s. This should ensure that any water droplets can fall through the steam in contra-flow, to the bottom of the vessel. Adequate height above the inlet is necessary to ensure separation. The separation is also facilitated by having the inlet projecting downwards into the vessel. The water outlet connection is sized to minimise the pressure drop from the vessel to the pump inlet to avoid cavitation. The flash valve connected to the vessel inlet is spring loaded for adjustment purposes.

Flash vessel optimisation is necessary in order to minimise the system pre-heat energy requirement. This is because energy invested in the preheating of the flash vessel is lost due to the nature of the diurnal cycle. The losses during the long overnight shutdown return the vessel to near ambient conditions each morning. A system optimisation is necessary in order to determine the proper capacity (size) and inventory (content) of the flash vessel. This would affect the start-up or pre-heat energy requirements of the system as the greater

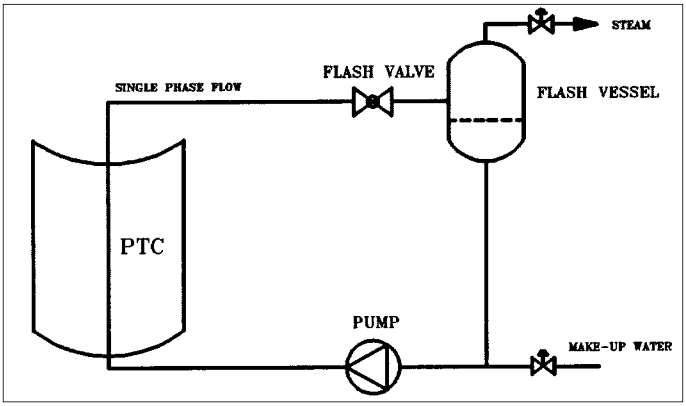

Fig. 1. The steam-flash steam generation concept

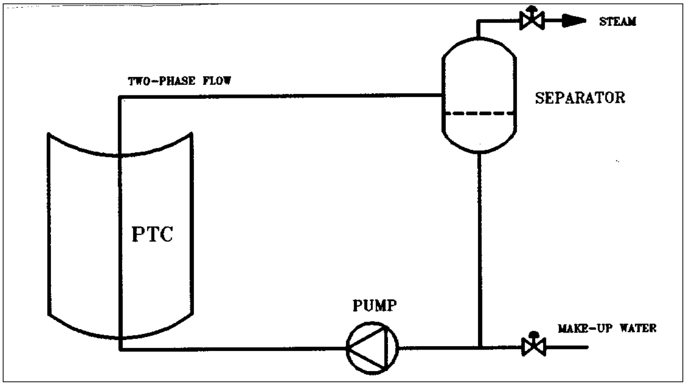

Fig. 2. The direct steam generation concept

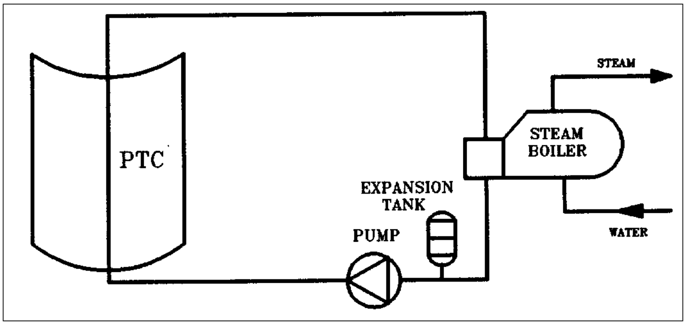

Fig. 3. The unfired-boiler steam generation concept

the water quantity the bigger the requirement. However, the system performance will drop (in terms of steam production) if the thermal mass of the system is reduced too much. This is because the addition of make up water would then "dilute" the system temperature and possibly result in the performance and hence production of steam becoming unstable.

The system refinement could be readily achieved by optimising the flash vessel water capacity and inventory and also by optimising the flash vessel dimensions and construction in order to lower the system thermal capacity and losses. One optimisation constraint which should be noted however, is the presence of a minimum water mass, of the circulating water, contained in the pipes, which is fixed and cannot be changed.

Another possibility which should be considered as a system refinement is the use of the flash vessel as a storage vessel. This will be done by oversizing the flash vessel and would have the advantage of starting the system in the morning with the water at a higher temperature but have the disadvantage of a greater water mass to heat up.

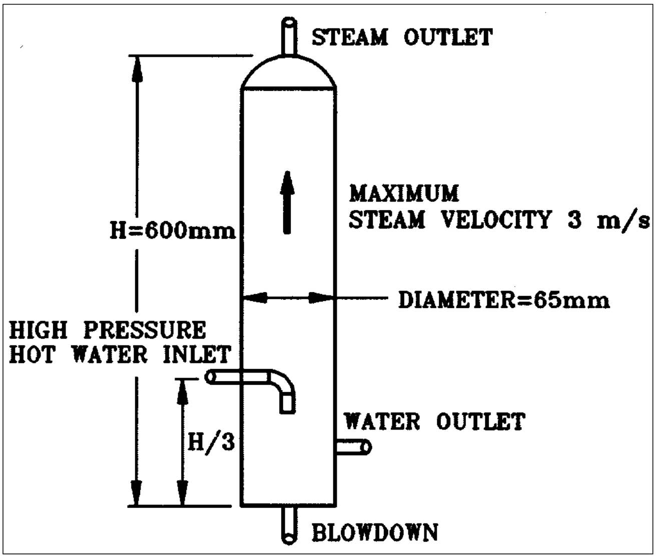

Fig. 4. Flash vessel design details

System optimisation is presented in Kalogirou et al. (1995) and may not be repeated here. The optimisation was performed with the use of a computer program developed by the author. The program takes into account the sensible heat requirement to increase the temperature of water from ambient to saturation, the thermal capacity of the various components of the system, and all the heat losses from the system. The program validation is also presented in Kalogirou et al. (1995) and it was shown that the program can simulate the flash vessel to within 6.5%. The optimised flash vessel dimensions and inventory for different collector aperture areas are shown in Table 1.

The logarithmic values of the collector area and of the flash vessel parameters, shown in Table 1, can be calculated and plotted. Thus Figures 5, 6 and 7 can be obtained. The actual data are shown by the small squares whereas the straight lines are obtained by the least square method. The equations of the parameters considered can be written as:

For the flash vessel inventory:

$$\log(I) = -0.751 + 1.101 \log(A) \Rightarrow I = 0.177 (A)^{1.101}$$

For the flash vessel diameter:

$$\log(D) = 1.507 + 0.425 \log(A) \Rightarrow D = 32.14 (A)^{0.425}$$

For the flash vessel height:

$$\log(H) = 2.709 + 0.174 \log(A) \Rightarrow H = 511.7 (A)^{0.174}$$

Collector Area (m^2)	Flash vessel diameter (mm)	Flash vessel height (mm)	Flash vessel inventory (litres)
10	75	800	2
60	225	1000	20
540	450	1430	160
2160	800	2080	850

Table 1. Flash vessel sizes obtained form system optimisation

Table 2 below lists all the constants of the equations 1, 2 and 3 together with the R^2-values and the correlation coefficients. These indicate how close to the best fit lines the actual data are. In all three cases the correlation coefficients are very close to unity which implies that the actual data can be represented by a straight line.

Flash vessel parameter	Graph intercept	Graph slope	R^2–value	Correlation coefficient
Inventory	−0.751	1.101	0.9963	0.998
Diameter	1.507	0.425	0.9797	0.989
Height	2.709	0.174	0.9756	0.988

Table 2. List of equations constants and correlation coefficients

During the design stage the collector area is first estimated according to the steam quantity requirements for the particular application. Subsequently the proper flash vessel should be selected for which either equations 1, 2 and 3 or figures 5, 6 and 7 can be used directly.

CONCLUSIONS

The three methods employed for solar steam generation are presented in this paper and analyzed with respect to their advantages, operating problems, operational stability, and cost. From the analysis presented in this paper, for low temperature applications, the steam-flash system is the most appropriate because it has advantages with respect to other systems due to the superiority of the water as a heat transfer fluid, the relatively low capital cost and the avoidance of any flow stability problems. The design of the flash vessel, which is the main part of the system, is then presented. Finally the flash vessel design graphs for the optimum flash vessel sizing are given. In particular graphs are given for the sizing of the flash vessel inventory, diameter and height. These graphs can be used directly for a quick design of a flash vessel up to a collector aperture area of about 2200 m^2.

REFERENCES

1. Hurtado P. and Kast M. (1984). Experimental Study of Direct In-Situ Generation of Steam in a Line Focus Solar Collector, SERI.
2. Kalogirou S., Eleftheriou P., Lloyd S. and Ward J. (1995). Optimization of the Initial Response of a Solar Steam Generation Plant, Proceedings of the 1995 ASME/JSME/JSES International Solar Energy Conference, Maui, Hawaii, pp. 513-520.
3. Kearney D.W. and Price H.W. (1992). Solar Thermal Plants-LUZ Concept (Current Status of the SEGS Plants), Proceedings of the Second Renewable Energy Congress, Reading UK, Vol. 2, pp. 582-588.
4. Murphy L.M. and Keneth E. (1982). Steam Generation in Line-Focus Solar Collectors: A Comparative Assessment of Thermal Performance, Operating Stability, and cost Issues. SERI/TR-1311.
5. Petterson P.J. and Keneth E. (1982). Flow Instability During Direct Steam Generation in a Line-Focus Solar Collector System, SERI/TR-1354.

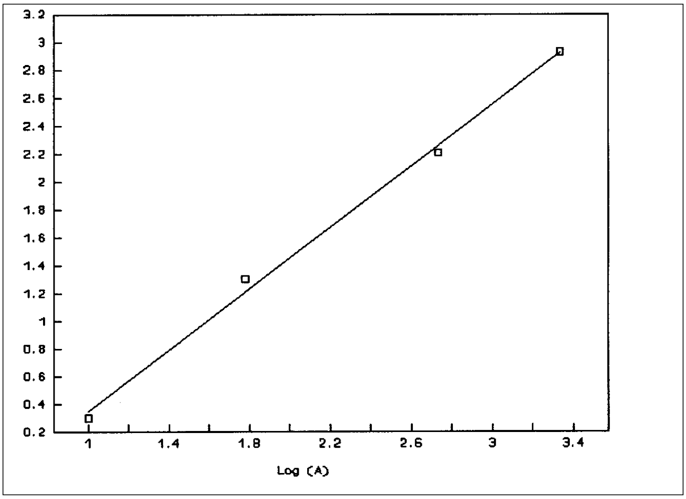

Fig. 5. Graph for estimating flash vessel inventory

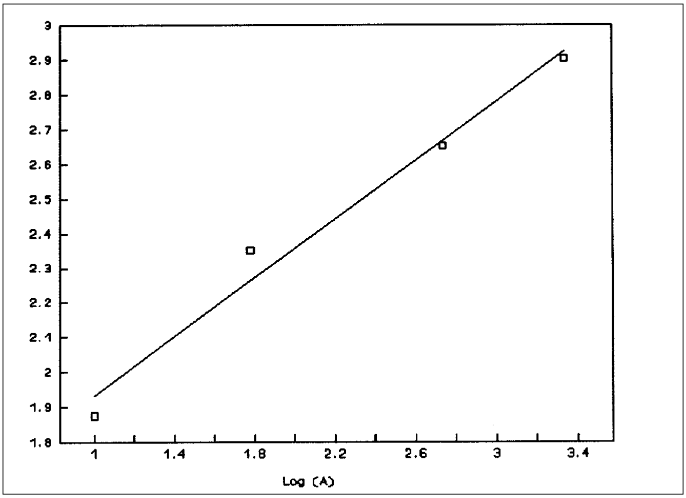

Fig. 6. Graph for estimating flash vessel diameter

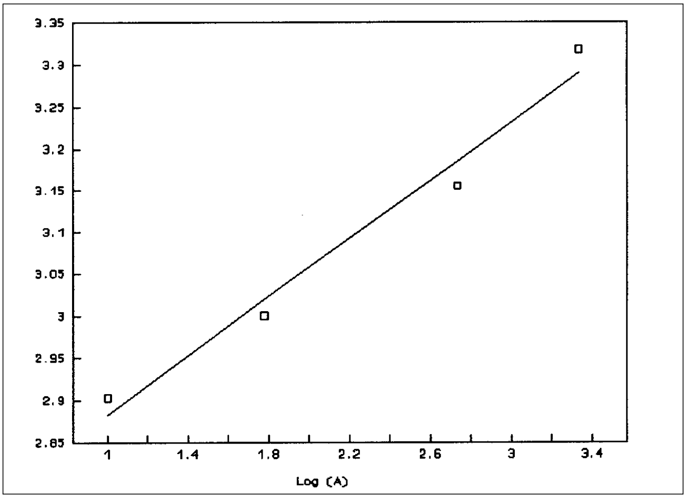

Fig. 7. Graph for estimating flash vessel height