TRANSIENT THERMAL PROCESSES IN SOLAR COLLECTOR/ STORAGE AND DISTILLATION SYSTEMS

by

Jayanta Kumar Nayak

Thesis submitted to the Indian Institute of Technology, Delhi
for the award of the Degree of
DOCTOR OF PHILOSOPHY

Department of Physics
Indian Institute of Technology, Delhi

December, 1979

Tvam Bhāno jagataschhakshuh,
Tvam ātmā sarvadēhinām,
Tvam yōnih sarvabhootānām,
Tvamāchārah kriyāvatām.

You, O Sun, are the eye of the world,
You are the soul of all embodied beings,
You are the source of all creatures,
You are the discipline of all engaged in work.

Yudhishthira in Mahābhārata

SUMMARY

This thesis presents the investigations of transient thermal processes in solar collector/storage and distillation systems; the theoretical analyses are validated by experiments performed by the author. The investigation on a single basin-type solar still with constant mass of water provides a theoretical basis for two well-known experimental results, viz.

i) The daily yield of the distillate is independent of the insulation in a ground still.

ii) The daily yield of distillate for large mass in the water basin is independent of the water mass.

With a view to increasing the efficiency of water distillation in basin-type still, a simple double-basin still has been proposed. The daily distillate production of such a still is on the average 36% higher than that of a single basin still. Two novel solar water heaters, which combine both collection and storage, have been discussed. These heaters can store substantial amount of heat, if these are insulated adequately during off-sunshine hours, to provide hot water in the next day morning. Performance evaluation and optimisation of system parameters for these water heaters have also been carried out. Transient analysis for rise of plate temperature in a flat-plate solar collector due to the accidental stoppage of fluid flow has been presented. It is found that under conditions of high

atmospheric temperature and intense solar insolation, the stoppage of fluid flow may result in the rise of plate temperature to a value large enough to exceed the maximum service temperature of inexpensive insulation when used below the plate and as a result such insulation may get damaged. Also the performance studies of Trombe walls and roof pond systems have been discussed. It is found that a thermal storage mass wall is preferable for larger heat storage duration while a water wall is suitable for rapid heat dissipation into the living space. A roof pond system comprising of water-concrete-insulation in ascending order of thicknesses in summer season and in descending order of thicknesses in winter season is found to be most desirable for Delhi climate; while the combination with ascending order of thicknesses is most appropriate for typical cold climate like Boulder, Colorado.

ACKNOWLEDGEMENTS

I wish to express a deep sense of gratitude to Prof. M.S.Sodha for his able guidance, many valuable suggestions and constant inspiration without which the present work would not have been possible.

I am also grateful to Dr. I.C.Goyal for his unstinting guidance and encouragement throughout the work.

I am thankful to Prof. S.S.Mathur, Prof. H.P.Garg and Dr. N.D.Kaushik for their active interest in the present work.

I am indebted to Dr. S.C.Kaushik for his valuable assistance and fruitful discussions throughout the work. Thanks are due to Dr.G.N.Tiwari for his suggestions and encouragement.

I would like to acknowledge the help rendered by Messrs Alok Srivastava, T.C.Kandpal, Ashvini Kumar, P.K.Bansal and Drs. N.K. Bansal, G.Umesh, A.K.Seth, Govind, Bhumesh Gupta and other members of the Centre of Energy Studies.

I am also thankful to Dr. A.R.Ray and Mr. S.K. Nanda for their encouragement given to me throughout the work.

I would like to thank Mr. T.N.Gupta for his elegant typing of the thesis and the manuscripts. Thanks are also due to Mr. Kirpal Singh for his help in preparing the figures.

The financial assistance by University Grants Commission and Government of Orissa is acknowledged.

Finally, I would like to record my gratitude to my wife, parents, sisters and brothers for their forbearance throughout the work.

Jayanta Kumar Nayak

(Jayanta Kumar Nayak)

PREFACE

Solar energy is an inexhaustible and viable alternative source of energy. Despite its highly decentralised, intermittant as well as diffused nature, it is capable of meeting a significant portion of human energy needs with a minimum adverse effect on the environment. Amongst the various modes of solar energy utilisation, the low temperature thermal conversion systems have received widest attention. Extensive investigations, scientific as well as technological, aimed at efficient use of these systems, have been made. The thermal-conversion devices essentially consist of a black absorbing surface, facing the sun, which transfers part of the absorbed energy to a working fluid in contact with it. To reduce heat losses to the surrounding environment, one or two sheets of glass are usually placed over the absorber surface; while the bottom and side surfaces are adequately insulated. Amongst the various applications of these devices, the simplest and most successful utilisation have been made in solar distillation and water heating.

Solar distillation, for the production of potable water from saline water, has been in practice for many years. The basin-type still dates back to 1872, when a large still was installed to meet the needs of a nitrate mining community in Chile. Later large-scale basin-type solar stills were installed in different parts of the world; however, at that time it was realised that the basin-type

stills could not compete economically with other methods of desalination for producing fresh water. But phenomenal increase in the cost of energy and other energy intensive modes of getting fresh water has triggered renewed interest in solar distillation. Recently, several community scale solar stills have been built and many advancements have been reported in the understanding and use of solar distillation. In order to reduce the cost of the distillate, different types of materials for transparent covers, basin liners and sealants have been tried out. Waste heat, in the form of warm water obtained from a variety of sources, have been used to augment the output of solar still. Apart from the conventional stills, different geometrical configurations have been tried out (Achilov et al., 1972; Coffey, 1975; Frick and Sommerfeld, 1973; Howe and Tleimat, 1974; Talbert et al.,1970); attempts have also been made to exploit the multi-effect concept (Dunkle, 1961; Ginnings, 1948; Hodges et al., 1966; Selcuk, 1964; Telkes, 1956) in solar distillation. However, it has been noted that in these cases the higher productivity is not desirable because of increased cost per Kg of fresh water (Howe and Tleimat, 1974; Talbert et al., 1970). Hence attention has been again focussed on basin-type stills with a view to improving the performance of solar distillation. Small scale (family size) solar stills of this type, for small isolated group of people, can produce potable water at costs that are

competitive with any other currently available desalination processes (U.N.Publication, 1970).

The experimental performance studies of basin-type solar stills, under different climatic conditions, have been made extensively (Baum and Bairamov, 1964; Bloemer et al., 1965; Cooper, 1969; Cooper and Read, 1974; Dunkle, 1961; Eibling et al.,1971; Garg and Mann, 1976; Howe and Tleimat, 1974; Sayigh and El-Salam,1977). Graphical (Morse and Read, 1968) as well as digital simulation (Cooper, 1969; Cooper, 1973) methods have been formulated to study the transient performance of the still. Theoretical model (Malik and Tran, 1973) has also been developed to analyse the nocturnal performance of the still. However, for estimating the daily as well as hourly production of a still, periodic solutions are desirable. Such solution has indeed been attempted by Hirschmann and Roefler (1970) and Baum et al. (1970). But in all these analyses, the solar insolation and ambient temperature have been expressed as a sine function (single harmonic) of time. This is, however, very inaccurate, since solar insolation and ambient temperature variations cannot be reproduced with one harmonic term alone. In the present thesis, a periodic analysis of the basin-type still has been presented; it considers the linearised Dunkle's relation (Dunkle, 1961) for heat and mass transfer and the solution of heat conduction equation in the insulation. It is seen that the

first six harmonics are adequate for a good representation of the observed periodic variation of temperatures and solar intensity. The results of the analysis have been found to be in good agreement with the experiments of the author and that of Cooper (1973).

The conventional still suffers from the disadvantage of a large area requirement per unit mass of water distilled. Also, part of the solar energy, absorbed in it, is used in solar distillation, while the rest is lost through the insulation (by conduction), below the basin liner and glass cover (by convection and radiation). Hence, for efficient solar distillation, improvement in the performance of conventional stills have been made recently. With a view to minimising the convective and radiative losses through the cover, a two-level double-basin solar still has been designed and tested (Lobo and Araujo, 1977). However, this still is difficult to fabricate, operate and maintain. This thesis proposes a simple double basin still, which on the one hand, minimises the convective and radiative losses occurring in conventional stills and, on the other, has a smaller area requirement per unit mass of water distilled. The experimental performance as well as the theoretical analysis of this still are also reported in the thesis.

The second part of the thesis is devoted to the study of solar water heating. All types of solar water

heaters in service to-date can be categorised into two groups:

a) collection and storage in separate units

b) collection and storage in a single unit

The conventional type of solar water heaters accomplish collection and storage in separate units and consist essentially of two elements viz. the solar collector and the storage tank. Domestic models of this type employ natural circulation of water and have gained popularity in Israel, Australia, Japan, South Africa and New Zealand. Large-size solar water heaters employ booster pumps for accomplishing circulation of water and are used for large scale installations in places such as hostels and hospitals. Considerable work has been carried out on the design, fabrication and testing of these systems by numerous workers (Buckles et al., 1979; Close, 1962; Czarnecki, 1958; Garg, 1970; Garg, 1973; Gupta and Garg, 1968; Harris et al., 1965; Klein et al., 1976; Malik, 1969; Morse, 1955; Shitzer et al., 1979; Whillier and Saluja, 1965; Yellot and Sabotka, 1964; Zvirin et al., 1977). However, separate insulated overhead-tank for storage of hot water in these water heaters places severe constraints on their use in the sense that

i) separate tank demands extra cost,

ii) the connecting pipe work adds to the thermal and frictional losses(Chauhan and Kadambi, 1976),

iii) overhead tank may cast its shadow on the collector surface especially at localities of low latitudes, i.e. the tropics, where the sun at certain times of the year moves north or south of overhead (Satcunanathan, 1973).

Also, for collectors, the fin effect has to be improved and a good bond between the plate and the tube has to be ensured. In view of these disadvantages, solar water heaters with collection and storage in a single unit have been proposed, developed and tested (Bar-Cohen, 1978; Chauhan and Kadambi, 1976; Garg, 1975; Satcunanathan, 1973). In order to codify these wide range of experimental results under different climatic conditions and hence to evaluate the performance of such collector-cum-storage water heaters, theoretical studies are of significant importance. Such attempts have indeed been made by Garg (1975) and Chauhan and Kadambi (1976). However, the former analysis suffers from an approximation of doubtful merit in the solution of the key differential equation, while the latter analysis deals with steady state solution. Hence, in order to predict the performance of such systems from a knowledge of meteorological parameters, a theoretical model has been discussed in this thesis. The theoretical results are borne out by the experiments of the author and by those of Garg (1975).

Another type of collector-cum-storage solar water heater has recently received wide attention. It differs from the type discussed earlier in having a water container

with transparent top and black bottom. Experimental performance of such water heaters have been carried out extensively by various workers (Gopfforth et al., 1968; Khanna, 1973; Kudish and Wolf, 1979). The principle of this type of solar water heater has recently been applied to large scale systems (Casamajor and Parsons, 1979; Dickinson et al., 1976), commonly known as shallow solar ponds,where water depth is small enough to rule out significant temperature stratification. However, none of these investigations include an analysis of the performance and consequent prediction of rise of water temperature with time from a knowledge of meteorological parameters. This thesis presents a model to predict the performance of the shallow solar pond water heater. An experiment has been carried out with such type of water heater; the theoretical results are found to be in good agreement with the observations of experiment performed and also with those of Kudish and Wolf (1979).

The application of flat-plate solar collectors to water heating and residential heating and cooling systems has been extensively investigated. Numerous models have been formulated to study the performance, to optimise the design and to evaluate the economics of those systems (Balcomb et al., 1975; Close, 1962; Collier, 1978; Gupta and Garg, 1968; Klein et al., 1976; Lof and Tybout, 1973; Nakahara et al., 1977; Ward and Lof, 1975; Woodman, 1977).

The present work includes a discussion of transient rise of plate temperature of a flat-plate solar collector due to the stoppage of fluid flow (which could occur accidentally). A simulated experiment has been carried out and observations are seen to be in good agreement with the theoretical results.

In addition to the above investigations, this thesis presents an analytical study of passive heating and cooling of buildings. Amongst passive systems (Balcomb et al., 1977; Balcomb, 1979), Trombe walls and roof ponds offer simple and inexpensive means of heating and cooling of buildings. However, the time dependent analysis of such systems does not appear to have been carried out. In the present work, the performance of thermal storage (solid mass and water) walls and roof pond systems has been analysed taking the periodicity of solar radiation and atmospheric temperature into account. Periodic heat transfer through walls/roof pond systems, exposed to periodic solar radiation and atmospheric air on one side and in contact with air at constant temperature (corresponding to air-conditioned rooms) on the other side, have been derived. Numerical calculations for the heat flux into the room have been made for typical (a) hot summer and (b) cold winter days in Delhi and (c) cold winter day at Boulder, Colorado.

A chapterwise summary of the thesis is as follows:-

Chapter-1: Periodic Theory of Solar Still

Since no satisfactory periodic analysis of the heat and mass transfer processes of a single basin-type still has been made so far, the author has analysed the performance of the still taking appropriate heat and mass transfer relations. Solar intensity and ambient temperature have been considered to be periodic and hence expanded as Fourier series in time; the first six harmonics are found to be adequate for a good representation of the observed periodic variation of temperatures and solar intensity. The Fourier equation of the heat conduction has been solved taking account of the periodic heat flux through the insulation to the ground or ambient air; in earlier treatments this was done rather arbitrarily, if at all. The results of the analysis are found to be in good agreement with the experiments of the author and that of Cooper (1973). They also provide theoretical basis for two well known experimental results viz.:

i) The daily yield of the distillate is independent of the insulation in a ground still (Bloemer et al., 1965).

ii) The daily yield of distillate for large mass in the water basin is independent of the water mass.

Chapter-2: Double Basin Solar Still

Because of the disadvantages of a large area requirement (per unit mass of water distilled) in conventional single basin type stills, a double basin still has been proposed. It differs from the conventional ones in having another sheet of glass fixed in between the basin liner and glass cover; this sheet serves as the base of an extra basin for saline water. The main advantage of this still is that the latent heat of vapour condensing over the lower surface of the lower glass cover, is utilised in heating the upper layer of water, rather than being wasted to the atmosphere (as is the case in conventional stills). On a typical winter day in Delhi the distillate output from such a still is 36% higher than that corresponding to a conventional still of the same area. A periodic theory has been presented to predict the performance of such a still and experiments have also been carried out with this type of still; the agreement between theory and experiment is fair.

Chapter-3: Performance of a Collector/Storage Solar Water Heater

The built-in-storage type of solar water heaters have not been theoretically analysed properly. This chapter presents transient analysis to predict the variation of temperature of water of these water heaters with time;

the analysis takes into account the appropriate heat transfer processes during the day and the night (when the top glass is covered by an insulation). Experiments have been carried out with such a water heater; these experimental observations as well as those of Garg (1975) for the variation of water temperature with time are found to be in good agreement with the theory.

Chapter-4: Performance of a Shallow Solar Pond Water Heater

This chapter presents an analysis and performance studies of a shallow solar pond water heater. The system consists of an insulated metallic tray with black bottom and sides and a glass cover at the top. After collection of solar energy during the day, the system stores substantial amount of heat because the top glass is covered by adequate insulation in the night. The experimental observation of the author as well as those of Kudish and Wolf (1979) for the variation of water temperature with time have been found to be in good agreement with the results of the theory presented.

Chapter-5: Transient Plate Temperature in Flate-Plate Solar Collector

In flat-plate solar collector the stoppage of water flow (which could happen accidentally) would result in a transient state when the temperature of the absorber may rise sharply. In this chapter the author has presented

a straight-forward analysis to find the transient temperature rise of the absorber plate as well as the temperature distribution in the insulation. A simulated experiment has been performed; the results are seen to be in good agreement with the theoretical results. It is concluded that the stoppage of water flow in a solar collector, under conditions of high atmospheric temperature and intense solar insolation (which occurs frequently in tropical deserts), may result in the rise of plate temperature to a value large enough to exceed the maximum service temperature of inexpensive insulation when used below the plate and as a result, such insulation may get damaged.

Chapter-6: Performance of Trombe Walls and Roof Pond Systems

This chapter presents an analysis of the periodic heat transfer through thermal storage walls and roof pond systems subjected to periodic solar radiation and atmospheric air on one side and in contact with room air at constant temperature (corresponding to air-conditioned rooms) on the other side. A one-dimensional heat conduction equation for temperature distribution in wall/roof has been solved using the appropriate boundary conditions at the surfaces; explicit expressions for the periodic heat flux through storage walls/roof have been derived. Numerical calculations

for the periodic heat flux into the room have been made to assess the relative thermal performance of storage walls and roof pond systems in both winter and summer seasons. It is found that a thermal storage mass wall is preferable for larger heat storage duration while a water wall is suitable for rapid heat dissipation into the living space. For Delhi, a roof pond system comprising of water-concrete-insulation in ascending order of thicknesses in summer season and in descending order of thicknesses in winter season is found to be most desirable; while the combination with ascending order of thicknesses is most appropriate for typical cold climate like Boulder, Colorado.

The work discussed in the thesis has been reported in the following publications/communications:-

1. Periodic theory of solar still, International Journal of Energy Research (In Press 1979).
2. Double basin solar still, Energy Conversion 20, No.1, (1980).
3. Performance of a collector/storage solar water heater, Energy Conversion 19, 41 (1979).
4. Physics of shallow solar pond water heater, International Journal of Energy Research (In Press, 1979).
5. Transient plate temperature in flat-plate solar collectors, Revue International d' Heliotechnique, 1er Semestre, p-8 (1979).
6. Note: Transient plate temperature in flat-plate Solar collectors, Ind.Jour. of Pure & Appl.Physics (In Press, 1979).
7. Performance of southfacing thermal storage walls and roof pond systems(Communicated, 1979).

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