SUMMARY AND CONCLUSIONS

Solar water heating with flat plate solar collector array to provide hot water at 60 - 90° C for industrial applications, hotels etc is gaining acceptance due to favorable economics. The collector area involved in such applications run into hundred of square meters to cater to high daily energy requirements. Modern trend in flat plate solar collector is to resort to internal-manifolded collectors and forming an array of these collectors in parallel. This arrangement has two distinct advantages :

- elimination of external insulated manifold, thereby reducing significantly installation cost and also array heat losses.

- reduction of collector array pressure drop, thereby pump size is reduced and consequently parasitic energy requirements.

Reduction in the collector array pressure drop can be appreciated by the fact that the ratio of pressure drop for collector purely in series to that in parallel is proportional to cubic of the number of the riser tubes, the number of tubes being identical in both the cases[Kutscher (1982)].

The use of several collectors in parallel, however, cause flow maldistribution for an improper collector geometry or unbalanced array, resulting in deterioration of collector efficiency as observed by Dunkle and Davey (1970) and Lydon (1979). Dunkle observed temperature differentials of 18°-22° C for collectors in parallel. Lydon observed similar trend for 12- and 18-module arrays where the temperature differentials were 30° and 45° C respectively. Lydon's experimental results indicate about 10 % loss in efficiency for the unbalanced 18-module array. Theoretical studies by Chiou (1982) indicate 2-20 % reduction in collector array efficiency depending upon flow distribution pattern.

Flow distribution is also affected by method of fluid feeding. The basic two methods of feeding are symmetric (or U-manifold) and asymmetric (or Z-manifold). In the symmetric mode, cold fluid enters at one end and exits from the same end. For the asymmetric mode, the fluid enters at one end and exits from the other end.

Generally, asymmetric feeding is preferred based on the fact that fluid in each riser tube covers the same path length from inlet to outlet. Collier (1976) and Pigford (1983) observed otherwise. This is due to the fact that system network and flow rates encountered are quite different, while both observation are correct in their own way. A solar system designer, however, requires a precise method to arrive at a proper design and performs optimisation to contain flow maldistribution in a large solar collector array thereby keeping array efficiency very close to that of a single collector.

The present work is thus addressed to the following :

- Formulation of a mathematical model for internal manifolded solar collector, both for symmetric and asymmetric array, to predict flow distributions in a large solar collector array.
- To verify experimentally the mathematical model by electrochemical technique
- To study the effects of collector geometry and system parameters on flow distribution.
- To suggest method of array balancing.

The present work will be also useful to an array of evacuated tube and concentrating solar collectors without phase change.

The thesis is presented in seven chapters, Chapter 1 is devoted to the introduction just described.

Chapter 2 presents the literature survey made on flow distributions in solar collector and in other fields.

The studies made so far for solar applications have been limited. But several studies have been made where flow is divided into parallel streams for processing e.g. in furnaces used for heating fluids in petroleum refineries and in some fixed bed catalytic reactors.

Chapter 3 describes the mathematical model of an internal manifolded solar collector. The behaviour of dividing and combining manifolds are discussed. The collector is considered as a pipe network consisting of dividing and combining manifolds interconnected by riser tubes. More important is the incorporation of the pressure changes at the tee junction. These pressure changes relate to the pressure rise at the tee junction in dividing manifold and presure fall in the combining manifold for the throughflow, and those for the dividing flow from manifold to the riser and the combining flow from riser to the manifold. Gardel's correlations (1957) have been employed to describe these.

The hydraulic network is then modelled by considering the resistance network equivalent to the pressure changes described above. Daniel algorithm (1956) is used to solve for the flow rates. The parameter which could be varied are the collector geometry and flow rate. Flow reversal can take place either when orifice balancing is attempted or for unfavorable collector geometry. This is also included in the model.

The effect of temperature on the flow distribution is also briefly described.

For known flow distribution the collector array efficiency is then determined by the method developed by Smirnov (1981). This method has been verified by Jiang and Mao (1985) experimentally.

Chapter 4 describes the analytical method used, that is electrochemical technique for flow measurement. The electrolyte used is 0.01 N potassium ferrocyanide, 0.01 N potassium ferricyanide and 0.5 N sodium hydroxide. The polarising current which is established between the test electrode and the reference electrode is a linear function of flow rate.

The high repeatibility and accuracy achieved by this technique was the reason for its selection for verifying the mathematical model.

Chapter 5 describes the experimental model set up used to verify the mathematical model developed in Chapter 3.

The set-up comprises of an HDPE collector, HDPE/PVC piping, pump, rotameter, 35 liter storage tank and the necessary pipe & fittings. The HDPE collector has 10 riser tubes of 20 OD connected to 50 OD manifold. This corresponds to an area ratio of 0.155. Copper test electrodes are provided in each riser and a relatively large reference electrode is provided at the outlet. A DC voltage is applied between the electrodes to measure the polarisation current in each riser which is propotional to the flow in the riser.

A calibration test set-up comprising of a single riser has been used to calibrate the flow, measured by a rotameter, and polarising current, measured by an accurate microammeter. The experimental set-up has a provision both for symmetric and asymmetric flow configurations.

Chapter 6 presents the experimental results and comparison with the predictions made by the model both for symmetric and asymmetric flow. The collector flow rates studied were in the range of 0.01 to 0.03 $kgs^{-1}m^{-2}$. The agreement between the theoretical and experimental results is excellent considering a difference of 4.5 to 7.5 % between the two. This also implies that Gardel's correlation for turbulent flow could be applied without any corrections.

The present model is also compared with the theoretical and experimental results of McPhedran (1983) for evacuated tubular solar collector with asymmetric flow. The agreement is excellent. The present model which is for isothermal conditions can, therefore, be employed with good accuracy for actual operating conditions.

The observations made on the experimental set-up can be summarised as follows:

-flow maldistribution increases with flow rate

-manifold pressure distribution in symmetric configuration is more favorable for attaining uniform riser flow.

-for a given collector geometry and flow rate it is possible to obtain practically uniform riser flow.

Having verified the model, flow distribution studies are made in a large solar collector array both for symmetric and asymmetric flow configurations. A widely used commercial solar collector is considered. The only collector geometry varied is the area ratio, which is defined as the ratio of the riser to manifold cross-sectional areas. The area ratios considered are 0.05,0.10,0.20 and 0.40. The riser diameter is kept fixed at 9.0 mm. The system parameter varied is the collector flow rate. The baseline flow rate is 0.0075 $kgs^{-1}m^{-2}$, and lower value of 0.0050 and higher value of 0.0150 $kgs^{-1}m^{-2}$ are considered.

The results are presented as the actual as well as relative riser flow rates. The relative riser flow rate provides a quick appreciation of maldistribution with respect to uniform value, and within limits extrapolation to other similar situation is possible. The pressure distribution in the manifolds are also presented to illustrate the flow behaviour. The collector array efficiency is described by Smirnov's method.

The observations can be summarised as follows:

The non-uniformity factor and thus the corresponding reduction in collector array efficiency is higher in symmetric flow. This is the reverse of the observation made for a single collector. The reason is that as the number of collectors in parallel increase the total flow rate entering the array also increases while keeping the collector geometry the same. The manifold pressure distribution is thus not the same, since the length to diameter ratio is altered.

To ensure similar pressure distribution it is necessary to increase the manifold diameter. This is effectively reducing the area ratio for the same riser diameter.

Uniform flow distribution is obtained by having a low area ratio both in symmetric and asymmetric flow configurations. Essentially, the riser pressure drop should be significantly higher than that across the manifold. This is obtained either by having low pressure drop manifold or high pressure drop riser.

Flow maldistribution increases with flow rate. For a given design i.e. no. of collctors in parallel, collector geometry and flow rate, lower flow rates can be used with more uniform flow distribution.

The upper header plays an important role in symmetric flow compared to that in asymmetric flow. Keeping the diameter of the upper manifold greater than that of the lower one helps in improving the flow distribution.

For low area ratios upto 0.10, both asymmetric and symmetric flow can be used, for 5 modules in parallel, with a reduction in collector efficiency not exceeding 1 %. For higher area ratios the drop in collector efficiency is significant and more so for symmetric flow, which could be as high as 13 % for area ratio of 0.40.

Three methods of balancing a collector array is reviewed, viz. area ratio, upper diameter greater than lower (in conjunction with area ratio) and orifice balancing for asymmetric flow. The simplest of these is the area ratio method. This is illustrated by studying the flow distribution in a collector array having 10 collectors in parallel and an area ratio of 0.05 and 0.10 in asymmetric and 0.05 in symmetric. The results indicate that indeed a low malditribution is obtained and the reduction in the collector array efficiency is only 1 % for area ratio of 0.05. Both symmetric and asymmetric can be used.

Chapter 7 presents the conclusions of the present studies,which can be summarised as follows:

- the model proposed here can accurately describe the flow distribution in a solar collector array. The model although derived for isothermal condition is also applicable for actual non-isothermal conditions provided the flow maldistribution is low.

- Area ratio is found to be the most important parameter in determining the flow distribution in a solar collector array for a fixed riser length. The desirable area ratio can be obtained either by fixing the riser diameter or that of the manifold.

- The flow distribution has been correlated to the collector array efficiency employing the Smirnov's method. This enables deciding the number of collectors which can be placed in parallel for a small reduction in the collector array efficiency, say, 1 %.

- The baseline collector and the flow rate are used widely in the industry with a very small variation. Thus, the findings of the present study can be universally applied.

- The isothermal model proposed has been found to predict very well the flow distribution in an evacuated solar tubular collector operating outdoors. The model can also be applied to similar situations such as a large array of concentrating collectors used in power generating plants.

- The studies in a large array indicate that both symmetric and asymmetric flow can be used with a very small reduction in the collector efficiency (less than 1 %). For 5-module in parallel area ratio upto 0.10 can be used. For 10-module an area ratio of 0.05 is required. In terms of porosity of the manifold a value of 4 or less is required.

- a simple balancing technique employing **'area ratio'** keeping the manifold diameters equal is found effective. Thus it is not necessary to have different manifold diameters or orifices for balancing.