2. LITERATURE SURVEY

Flow maldistribution in a solar collector array was first studied by Dunkle and Davey (1970). They made an approximate analysis of a solar collector array employing isothermal model. In their analytical approach, the individual risers were replaced by a distributed flow resistance between the headers. This permitted a general analytical solution of pressure and flow distribution which will correspond closely to the actual distribution in a large collector array. This could, alternatively, be visualised as replacement of separate risers by an infinite number of risers offering the same total resistance to flow, but having the effect of varying the flow continuously along the headers rather than in a series of steps corresponding to flow in each riser. Thus, greater the number of risers in an installation, better the mathematical approximation to the real system.

Assumptions made by them, other than the system being isothermal, were :

1. Turbulent flow in the headers and laminar in the risers.

2. Effect of density variation with temperature on the flow distribution was neglected.

Regarding the first assumption, they claimed that even at low Reynolds numbers, the form drag due to the risers projecting into the header and flow disturbance at the absorber interconnection will justify the assumption of turbulent flow in the header throughout. For large collector array in parallel, most of the risers will operate in laminar flow and thus a few extreme risers with turbulent flow will not affect analysis in a significant manner.

Dunkle and Davey had analysed only single configuration, that is, asymmetric or Z-manifold (see Chapter 1 for definition of flow configuration). Their analytical solution indicated that :

a. for high pressure drop in the headers relative to the risers:

- more flow in risers tended to concentrate towards the extreme risers at both the ends of the array with lower flow in the middle ones.
- pressure drop varied linearly with distance in the header, that is, flow is uniformily distributed between the top headers with cross flow concentrated in the extreme risers.

b. for high pressure drop in the risers relative to the header:

- flow was distributed uniformly in the risers.
- pressure drop varied with cube of distance along the top headers.

Their experimental investigation involved measurement of tempe rature of the risers at three fourths along the flow, of an array having 12 collectors in parallel. The area of each collector was 8 ft^2 corresponding to 4 ft long x 2 ft wide absorber (with selective surface). The flow rates employed were 60, 90 and 120 gallons per hour. Alternatively, this can be expressed conventionally as 25, 37.5 and 50 $kgh^{-1}m^{-2}$.(*)

It may be noted that the collector module used by them was very small relative to the ones used presently of 2 m^2 or about 22 ft^2, nearly three times the area used by them.

Temperature distribution in the 12 module collector array indicated that temperature was high at the centre implying little water was flowing up the centre risers, the bulk of water passing through the first and end few risers. Temperature difference between extreme and middle risers increased with flow rate.

They suggested series - parallel arrangement to minimise flow maldistribution, e.g. keeping 4 collector modules in parallel and such arrangement in series by inter-connecting pipes. (This involves additional insulated piping thus increase in cost. Also this results in an increase in pressure drop).

(*) The area referred here is the absorber aperture intercepting the incident solar radiation.

Dunkle and Davey's experimental work was quite preliminary in the sense that the measured temperature distribution indicated the expected flow distribution, and no attempt was made to correlate theoretical and experimental data. Their work, however, raised a pertinent problem of flow maldistribution in a large solar collector array and the degradation in the thermal efficiency.

Rohde and Knoll (1976) analysed a very large solar collector array with a total area of 1399 m^2. The solar collector array consisted of 51 collector panels connected in parallel between inlet and exit collector manifolds to form one row. Twelve such rows were in turn connected in parallel between the main inlet and exit field manifolds to complete the field. The investigations carried out by them dealt with both the flow variation inside a row from collector panel to collector panel and the overall field flow variation from row to row. Various factors which influenced these flow distributions, such as various size manifolds, area change along the manifold, different locations of the inlets and exits to the manifolds and orifices or flow control valves, were studied.

The collector description was not given, but it was evident from their work that they employed a collector of the type shown in Fig. 1.1 (a) or Fig. 1.1 (b) since they employed separate exit and inlet collector manifolds of 40.89 mm and each collector provided with an orifice wherever necessary for flow distribution control. For the purpose of analysis they had considered a collector panel with a maximum flow resistance of 0.17 Ncm^{-2} or 1700 Nm^{-2} (0.25 psi) for flow of 31.5 cc/s (0.5 gal/min) or 113.4 kgh^{-1}.

For the purpose of network analysis, they had lumped three collector panels into a single equivalent resistive element. Two types of coolant feeding were considered, firstly asymmetric or Z-manifolding and secondly centre feed. The latter involved basically each collector row divided into two halves, each half with symmetric or U-manifold flow configuration (see Chapter - 1 for definition of flow configuration). The total feed flow rates studied ranged from 2271 cc/s to 22712 cc/s or 8176 to 81760 kgh^{-1}. This is equivalent to 5.84 $kgh^{-1}m^{-2}$ to 58.4 $kgh^{-1}m^{-2}$.

The mathematical model employed by Rohde and Knoll (1976) was essentially very simple by considering pressure changes attributable to manifold friction pressure losses, manifold momentum pressure changes, orifice flow control pressure losses and collector panel losses. The flow in collector panel was assumed to be turbulent. The simplicity of their module lied in the fact that pressure drop in a collector or row of collectors is the overall value for the element with respect to flow, which they claimed to have been verified by experiments. Thus, they apparently had not analysed based on collector or row detailed geometry. The overall network model for each collector row and the total field was iterated on the flow rate re-estimated from calculated pressure distribution.

The results of their study are summarised below :

Collector Row

(a) The pressure distributions in the collector manifold were similar to the one calculated by Dunkle and Davey (1970) resulting in higher flow rates in the extreme collectors in a row with gradual decrease towards the middle ones. This was due to excessive frictional pressure drop in the manifolds.

(b) Turbulent flow in the collector panel caused lower maldistribution than laminar flow.

(c) Four solutions were investigated to reduce maldistribution :

* Increase the collector manifolds size.
* Change the method of feeding water to the manifolds.
* Utilise stepped manifolds (a manifold with a change in cross-sectional area).
* Utilise orifices to control the flow.

The results of the four methods suggested are given below :

(d) Increasing the diameter of the collector manifold reduced flow maldistribution. (This is expected since collector pressure drop becomes more dominant with reduced frictional pressure drop in the manifolds which results in balancing effect).

(e) Changing feed system from asymmetric to centre-feed reduced flow maldistribution. (However, this is not a good comparison since the number of collectors were halved in case of centre feed system.)

(f) Stepped manifold reduced flow maldistribution (again for the reasons of reducing frictional pressure drop in the collector manifolds).

(g) The last solution, which was finally selected on the basis of lowest initial system cost, utilised sharp edged orifices in series with the collector panel to throttle the flow through the higher flow panels of the asymmetric feeding system. The flow maldistribution was significantly reduced. In this case, pumping power increased. Also variation from the design flow rate resulted in higher maldistribution.

Collector Field

The feeding of the collector rows by the field manifolds was symmetric (or U-manifolding). The pressure distribution was similar to the one expected with this kind of feeding, i.e. the first row of collector received maximum flow which diminished towards the last row.

Again flow variation was reduced either by increasing field manifold or by orifice or valves to control flow into the rows. The latter was adopted by Rohde and Knoll (1976) to keep initial costs of manifold low. They preffered valves since the rows could be balanced at different flow rates. They also suggested that asymmetric feeding of the rows would reduce flow variation (without control valves).

They had not verified their predictions experimentally. The results , however, indicated flow distribution pattern observed by others.

Lazzarin et.al (1976) investigated flow pattern experimentally in a single roll bond collector with IR thermography. Their studies also revealed flow maldistribution which resulted in 4-5% drop in efficiency. Their contention was that the assumption in Hottel - Whillier-Bliss equation of uniform flow was no longer valid for such collector design. Collector flow rates studied were 44.5, 89 and 154 $kgh^{-1}m^{-2}$, relatively high flow rates.

Bajura and Jones (1976) had studied flow distribution in the lateral branches of dividing, combining, reverse and parallel flow manifold systems both analytically and experimentally. A continuous model was proposed. Good agreement was obtained between the theoretical and experimental results. The experiments was done with air. The parameters found to affect the flow distribution and the observations made were :

1. Area ratio (porosity) - defined as the ratio of the total lateral (or riser) cross-sectional area to that of the manifold. Large area ratio contributes to flow maldistribution. The rule of thumb is to keep it less than one.

2. Lateral (riser) flow resistance - An infinite lateral flow resistance would cause even a small diameter manifold with large

porosity to act as an infinite reservoir. Thus, large lateral resistance contributes to uniform flow distribution.

3. Length/Diameter Ratio of Manifold - For headers of relatively small length/diameter ratio, the effects of friction may be neglected and the flow distribution equation can then be solved analytically. For relatively long headers, the effect of flow branching on the static pressure in the header can be neglected.

4. Momentum Parameters - The parameters are relatively fixed. However, as the lateral to manifold diameter ratio increases to 0.5 the parameter becomes highly variable. The values in the analysis were kept fixed since normally most of the systems are designed with diameter ratios about 0.15.

5. Diameter ratio - Selection of larger combining manifold diameter helps in obtaining uniform flow distribution, since momentum coefficients are reduced by increasing the diameter. The momentum coefficients are more important than friction in determining the flow distribution. The reverse results in flow maldistribution.

The tests were done on 10 or 20 lateral points. The results indicated that reverse (symmetric) flow was better than parallel (asymmetric) one when the dividing flow manifold was dominated by pressure recovery and friction effects were minimal. A parallel flow gave better flow distribution than a reverse system if friction effects dominated the dividing flow manifold (but this was not necessarily so). In general, flow distribution in reverse flow system was better than parallel one. The total pressure loss for reverse flow was lower than parallel one.

Lydon et.al (1979) emphasized that flow imbalance could seriously affect collector performance. Theoretical model was not described by them, but they made computer model estimates which showed that unbalanced large collector array performance deteriorated with increase in collectors in parallel. They had not described the collector geometry. Lydon's experimental results did not agree with the computer model. The experimental results, however, indicated significant drop in array performance for 18 collector array in parallel. The flow configuration studied was asymmetric and the flow profile was similar to the one observed by Dunkle (1970), i.e. higher flow in the extreme risers and lower in the middle ones. Lydon, therefore, suggested to place calibrated orifice elements termed as 'balancing inserts'.

The 'balancing inserts' were placed in the upper header at the collector inter-connection for collectors in the left half of the array and in the lower header for the right half of the array. Effectively, flow was restricted to extreme collectors and diverted to the middle ones. Properly calibrated balancing inserts and required numbers ensured that each collector gets nearly equal flow. The collector flow rate range studied by them was 56 - 112 $kgh^{-1}m^{-2}$.

Smirnov et.al. (1981) made a simple analysis of the effect of flow maldistribution in a solar collector array, both for asymmetric and symmetric feeding. Collector array eficiency was derived based on the collector heat removal factor, which was the ratio of specific collector heat removal factor for an array with flow maldistribution to one without any. The reduction in the array efficiency derived was 5 - 8.5 % depending upon type of collector.

An experiment was conducted by them on an array comprising of 4 collector in series arranged in parallel branches, thereby total number of collectors were 40. The collectors used were of the type shown in Fig. 1.1 (a) or (b). Complete description of the collector geometry and array manifolds were not given. The collector flow rates employed were 5 - 30 $kgh^{-1}m^{-2}$. The flow rate in each branch was deduced from the temperature measurements of inlet and outlet of each branch. They observed that both for symmetric and asymmetric feeding the computed branch flow rates were not very far from the uniform value, especially for total collector rate of 5 $kgh^{-1}m^{-2}$.

The experimental observation above is expected in view of series-parallel configuration used. Four collectors in series increased the branch resistance. Their configuration is not of direct relevance to the present work on internal-manifolded collector. Their analysis of collector array efficiency is of interest and utilised in the present study for estimating collector array efficiency for known flow maldistribution.

Chiou (1982) analysed internal manifolded solar collector comprising of 10 risers. A detailed 2-D model was developed to estimate the collector efficiency due to flow maldistribution. The effect of collector parameters such as absorber thermal conductivity, meteorological factors - solar flux, wind velocity, ambient temperature, and collector flow rate were studied.

Various flow patterns in the collector risers were assumed rather than calculated. The assumed flow distribution was characterised by a non-uniformity factor, which is equivalent to standard deviation. This was correlated to the collector efficiency degradation. It was observed by Chiou that the collector degradation varied from 2 to 20 % depending upon flow pattern.

An excellent treatise in piping manifolds similar to internal manifolded solar collector has been done by Pigford et.al. (1983). They have analysed theoretically flow in parallel pipes, both for symmetrical or U-manifolded and asymmetrical or Z-manifolded in turbulent region. The agreement with experimental data was excellent. They observed that uniformity of flow rates among the parallel pipes of a piping manifold was governed by the variations in fluid pressure inside entrance and discharge manifold. These resulted from fluid friction and from loss or gain of fluid momentum at the exit and entrance ports (tee junctions, i.e. where the pipe meet the manifolds at either end)

Pigford´s (1983) experiments involved air and encompassed highly turbulent range of flow. The theoretical and experimental findings nevertheless, depict the parallel pipe flow behaviour. The major findings were as follows.

U-manifold (Symmetric)

1. Greater values of pipe pressure drop leads to flow uniformity.
2. Greater manifold pressure drop leads to flow non-uniformity.
3. As the flow distribution deteriorates the pressure drop rises above the value expected for uniform flow distribution.

Z-manifold (Asymmetric)

1. The flow uniformity and excess total pressure drop behaved in similar way to that of U-manifold.
2. The flow distribution among the pipes was qualitatively different from that in a U-manifold. The pipe carrying minimum flow vary at either end or between. If manifold friction pressure drop was zero, the minimum flow occured in the middle and the distribution was nearly parabolic. As frictional pressure drop in manifold increased the minimum flow point moved towards inlet. However, as pipe pressure drop increased the opposite occured.

Pigford gave a general thumbrule stating that the manifold cross-section area should be greater than that of the total pipe area, but this alone was not adequate as the flow uniformity was governed by the flow resistance of the pipe also.

Comparatively, Pigford observed that flow non-uniformity were greater for Z-manifold than for U-manifold for the same number of parallel pipes, pipe and manifold pressure drops.

This was an interesting observation which is normally contrary to the common understanding ,or rather thumb rule. A similar observation was made by Collier (1976) in a parallel four pipe network for total flow rate of 8000 to 18000 lb/h. Collier also contended that uniformity could be obtained by keeping pipe area smaller than manifold and by keeping head loss in the pipe much greater than the inlet velocity head into the manifold.

An extensive analysis of flow distribution in evacuated tubular solar collector was carried out by McPhedran (1983). The theoretical model developed was a continuous one, that is , the risers were not considered as discrete entities and the pressure changes along the manifold was smooth. The pressure change in the manifold was thus represented by a differential equation. This is quite similar to the model of Dunkle and Davey (1970). McPhedran´n model was, however, more generalised and had the following salient features:

- Bernoulli˙ effects in the manifold was allowed for.
- Flow in the manifold was Reynolds number dependent.
- Flow in the riser was laminar
- Momentum conservation rather than energy one was employed for modelling tee junction.

In these respects, the model developed by McPhedran was advanced. Both symmetric and asymmetric flows were considered. Being a continuous model, the number of risers, **N**, was important only as far as it affected the total flow rate, Q_T, and the common header length, **L**. This was because the total flow rate in the collector was scaled according to the number of risers in order to keep the temperature gradient across each riser uniform. The flow rate of 1 l/min was considered for each 15 risers.

Thus, if **L** and Q_T were held constant, then variation of **N** had no effect on the computed flow pattern. In an actual manifold, this would not be the case, since various flow parameters appropriate at each riser-manifold junction would be affected by the conditions prevailing around all other junctions. This inherrent error, McPhedran expected to be small for **N** exceeding 10 or 15.

The findings of McPhedran are summarised below :

a. If there is uniform flow, the pressure drop across the risers should significantly exceed the pressure drop across the manifold.

b. In manifolds where Bernoulli effects on pressure are significant, the outlet manifold is more critical than the inlet one. This is because, in the inlet manifold, the flow is dropping off continuously leading to a Bernoulli regain of pressure opposing the frictional loss, whereas the increasing flow in the outlet manifold leads to a Bernoulli drop in pressure reinforcing the frictional loss. Thus, an optimal manifold design would have inlet and outlet manifolds diameter chosen to equalise their pressure drops.

c. Except for low number of risers (15), flow distribution degrades by going from asymmetric to symmetric flow. This is due to higher frictional losses of pressure in the manifold compared to Bernoulli pressure change for the collector geometry considered.

d. The ratio of riser diameter to that of manifold is the most important choice in the design of collector manifold.

McPhedran carried out outdoor experiments with evacuated tubular solar collectors. Flow rates were not measured directly, but were calculated from the observed temperature rise across the risers. Experiments were made both for asymmetric and symmetric flows. Agreement between theory and experiment was excellent.

Soin (1983) proposed a hydraulic network model to predict flow distribution in an internal manifolded solar collector array. Both symmetric and asymmetric flow configurations were studied. The model accounted for the frictional losses in the riser and manifold, and more important was inclusion of pressure losses at the tee junction of riser and manifold. The model incorporated the effect of collector geometry, more specifically the area ratio, which was defined as the ratio of riser to manifold cross-setional area, effect of collector flow rate, and also allowed flow reversals in the risers. The model was essentially isothermal. The following summarise the theoretical predictions :

a. Effect of flow rate

- For any area ratio, flow maldistribution increases with flow rate. For small area ratio, the effect is negligible which increases pronouncedly as the area ratio increases.
- For low number of collectors in parallel the flow maldistribution is lower in symmetric flow compared to asymmetric. The reverse is true for large collector array.

b. Effect of area ratio

For a given manifold, decreasing the riser diameter or area ratio, effectively increases the riser pressure drop which helped in reducing flow maldistribution. This is true for any flow rate and flow configuration.

c. In general, the flow distribution pattern in a collector array with asymmetric flow configuration indicates higher flow rates in the end risers with minimum in the middle ones. The minimum is towards the exit which shifts further with flow rate. The last riser, next to the exit, has the highest flow rate.

In case of symmetric flow, the flow rate was maximum in the first riser (next to the inlet/exit) and decreases towards the last riser.

d. By a proper selection of area ratio flow maldistribution could be kept very low such that the degradation in the collector efficiency is less than 1 %.

The theoretical predictions were not validated by any experiments.

Culham and Sauer (1984) examined the effect of unbalanced flow on the system thermal performance. Their analysis, however, was restricted to the effect of imbalance in rows of collector constituting an array, rather than within a row. In a row it was assumed that the minimum riser flow rate was 35 % (or more) of the recommended flow rate and the pressure drop across the riser was at least 10 times greater than that across the manifold. The flow configuration was asymmetric (reverse-return). The model used to estimate the effect of flow imbalance on the system thermal efficiency was quite simple which lumped all the collectors in a row into a single equivalent collector. This obviously neglected flow distribution within the row. Further, the authors did not elaborate the assumption made regarding keeping the minimum flow rate. Apparently, this was based on the values of $F_R U_L$ (product of collector heat removal factor and overall loss co-efficient) of about 0.90 for flow rate of 35 % of the rated value. This being a minimum, effectively higher values could be obtained for the collector since higher flow rates would be encountered in the remaining risers.

Saman and Mohammed (1985) analysed a single collector as a pipe network to obtain flow and temperature distribution. They varied flow rate in the collector, number of risers per unit width of collector, the ratio between bottom to top header diameters, the ratio between header to riser diameters and loss factor.

They presented the results of increasing the number of risers on flow distribution at a particular flow rate. The results showed that riser nearest to the outlet always carried the highest flow rate and maldistributon increased with increase in number of risers. Based on the predicted flow distribution, the temperature in the risers were also estimated and compared with the values which would have been if uniform flow was observed. The loss of efficiency was not reported.

Saman and Mohammed (1985) also carried out experiments on a single collector of 1.8x0.8 m having 26mm manifold (header) and 13 mm risers. Both symmetric (U-manifold) and asymmetric (Z-manifold) flow configuration were studied. The temperature rise at noon and pressure-drop in the risers were measured. The flow in the risers were deduced from pressure drop data.

They observed that:

* In asymmetric mode, flow maldistribution increased with collector flow rate (10 - 180 $lh^{-1}m^{-2}$) quite significantly.

* In symmetric mode, flow maldistribution was lower than in asymmetric mode. Also, flow maldistribution was not affected profoundly with increase in flow rate (10 -180 $lh^{-1}m^{-2}$).

It is interesting to note that Saman and Mohammed (1985) also observed that under identical conditions flow was more uniform in symmetric rather than in asymmetric mode for a single collector. They, however, had not compared the theoretical and experimental results, except for the total pressure loss in the collector. They found that the loss factors assumed for unrounded edges at the riser - manifold junction had to be corrected to 30 % of the values for unrounded edges. It was reported that further work was being done to estimate the effects of flow maldistribution on the collector efficiency.

Hoffman and Flannery (1985) developed a theoretical model to determine the flow distribution in a solar collector array. The model comprised a system of simultaneous non-linear equations for internal manifolded solar collector. The model allowed variation in header and riser sizes, fluid type and viscosity, flow rate and number of collectors in parallel. The theoretical model predicted U-shaped distribution with end risers having higher flow rates than the middle ones. Greater the number of collectors in parallel, deeper was the U-curve.

Experimental verification was carried out on a full scale collector piping grids. The flow rates were measured by means of calorimetric flow-meters. The flow rates studied were 50, 100, 200 and 300 % of the manufacturer's rated flow. The measured flow distribution was similar to one predicted.

The results were presented in a graphical form. The critereon for selecting header-riser combination for given number of collectors in parallel was that the minimum acceptable flow rate in the riser should be 35 % of the rated flow as suggested by Culham (1984). The collector had 1.98 m long riser and 8 risers in a collector.

The authors had not discussed in detail the experimental verifications of their model. Like Culham (1984), they did not elaborate the choice of minimum flow rate of 35 % of rated flow.

Jiang and Mao (1985) presented experimental results on a 9-collector array, arranged in series, parallel and series-parallel. They determined the effect of the configuration on the collector efficiency. They used a coefficient to describe the collector array efficiency due to maldistribution as suggested by Cawphob (1982) similar to one derived by Smirnov et.al. (1981). This factor could not be used directly by them since flow distribution was not known. Instead, they were assumed as suggested by Cawphob, irrespective of flow rate. Their theoretical calculation for 9-collector array in parralel in asymmetric showed interesting results :

a. Array collector eficiency degradation increased significantly with decrease in total collector flow rate. This was closely related to temperature rise in the individual collectors, since lower-flow rate implied higher temperature rise and lower collector efficiency.

b. At higher collector flow rate the temperature differential* was higher and was relatively lower for lower flow rates. For example, at 0.099 kgs^{-1} total flow rate the temperature differential was 49.8° C at radiation level of 900 Wm^{-2}, 47° C at 0.0045 kgs^{-1} and 800 Wm^{-2}, and 27.2° C at 0.01953 kgs^{-1} and 700 Wm^{-2}. Of course, radiation level affected the temperature differentials, but the authors did not keep it constant. This was because they wanted to adjust flow rate to keep outlet temperature constant for the single pass system.

The calculated array oulet temperatures for the above three radiation values were 34.4, 41.2 and 54.1° C respectively. The authors did not elaborate this variation. Direct comparison is therefore difficult. The collector array efficiency degradation were 6, 8.5 and 9 % respectively. It increased further if the array outlet temperature were to be kept the same as that obtained from individual collector analysis. This necessarily required increase in the total flow rate. The corresponding collector array efficiency degradation were 6, 12 and 18 % respectively.

* temperature differential is the difference of the maximum and minimum riser outlet temperatures.

The actual experimental efficiencies agreed very closely with the above observations.

It was observed that the collector array efficiency degradation was significant. It would have been very useful if the authors had elaborated further thèir theoretical calculations and the experimental results to explain the effect of flow maldistribution. Also, instead of comparing collector efficiencies it would have been interesting to compare the actual flow rates and temperature distribution, since the collector array efficiency was determined strongly by the flow distribution. Nevertheless, since the experimental array efficiency closely matched the theretical one, two conclusions could be drawn :

a. Collector array efficiency degradation was significant for collectors in parallel.

b. The coeeficient derived by Cawphob (1982) or Smirnov (1981) could be utilised to estimate the loss in collector array efficiency for a known flow distribution.