Evaluation of the Performance of a Collector Array in a Once-Through Solar Water Heater

Jian Min JIANG* & Yin Qui MAO**

GanSu Natural Energy Research Institute
Lanzhou, GanSu Prov.
China.

ABSTRACT

Once-through solar water heaters have been extensively used in China and some other countries. To investigate the effect of different collector configurations, a once-through system incorporating nine flat plate collectors was constructed in Lanzhow, China, in 1982. The performance of this system has been monitored to determine the effect of series, parallel or combined collector connections. The results show that the concept of instantaneous efficiency of a single collector can be used to evaluate the performance of a collector array.

INTRODUCTION

Once-through solar water heaters have many advantages over recirculating systems. In particular no recirculation pump or plumbing is needed since the supply water pressure can be used to control the collector flow rate. Another major advantage of once-through systems is that high temperature water is available earlier than for pumped or thermosyphon recirculation systems. (typically 40°C to 50°C at 10:00 a.m. in Lanzhou compared to 4:00 p.m. for the same temperature with a recirculating system).

Although the once-through system has been widely used in China, there are no design methods available to predict the performance of different system configurations. To obtain data on the performance of these systems, the GanSu Natural Energy Research Institute has been monitoring the operation of a series of once-through systems since 1982.

ONCE-THROUGH EXPERIMENTAL SYSTEM

A system of nine flat plate collectors was built and operated in Lanzhou, China, 103°51′E longitude, 32°2′N latitude. The collector flow rate was controlled by a constant pressure water supply and a series of 31 valves so that the system could easily be arranged as either series, parallel

*At present on leave at Solar Lab, Department of Mechanical Engineering, College of Engineering and Applied Science, Arizona State University, Tempe, AZ 85287. U.S.A.

**At present on leave at Solar Energy Group, Department of Mechanical Engineering, University of Melbourne, Parkville, Victoria, 3052, Australia.

or combined connection of the collectors (Fig. 1). The collector array was inclined at 29° to the horizontal and oriented 16.3° southwest. The collector characteristics are given in Table 1. Individual collectors were tested on the outdoor test rig at the GanSu Natural Energy Research Insti-

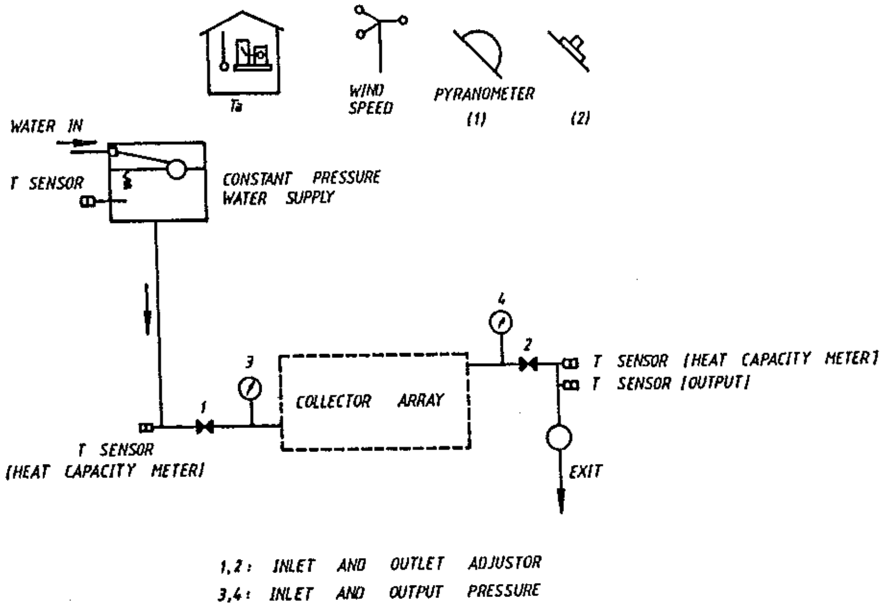

Fig. 1 Structure of the system

Table 1. Collector characteristics

Cover material	:	glass
Number of covers	:	one
Absorber plate		
material	:	0.8 mm mild steel
coating	:	black paint
riser tubes	:	14 mm mild steel
Distance between riser tubes	:	100 mm
Riser tube-plate connection	:	tube above the plate and spot welded connections
Insulation	:	fibre glass
Thickness – back	:	45 mm
sides	:	35 mm
Aperture area	:	1.668 m²
Overall dimensions	:	1692 × 1170 × 100 mm
Time constant	:	5 minutes.

tute. For a collector flow rate of 0.02 kg/m^2 s, the collector efficiency was:

$$\text{Efficiency} = 0.698 - 6.84 \frac{(T_{in} - T_a)}{G_T}, \quad (1)$$

or

$$\text{Efficiency} = 0.727 - 7.13 \frac{(\bar{T}_w - T_a)}{G_T} \quad (2)$$

INSTRUMENTATION AND TEST METHODS

The collector array performance was measured when the following quasi-steady operating conditions were achieved over a fifteen-minute period.

(i) ambient and inlet temperatures changed by less than 0.5°C.

(ii) radiation was greater than 500 W/m^2 and changed by less than 5%.

(iii) wind speed was less than 2 m/s.

(iv) fluid flow rate changed by less than 5%.

The fluid temperatures were measured with platinum resistance thermometers with errors of less than 0.25°C, and the ambient temperature was measured with a mercury in glass thermometer with an error of less than 0.2°C. The product (mC_p) was measured directly with a heat capacity meter with an error of less than 1.5%. The radiation intensity in the plane of the array wa measured with an Li-175 and a Rs1008 pyronometer with errors of less than ±5%.

The following three collector array configurations were tested (Fig. 2):

(i) 9 collectors in series

(ii) 9 collectors in parallel

(iii) 3 parallel collectors and 3 series banks (symbolized 3 X iii).

The instantaneous efficiency characteristics of each array were measured and the day-long output was also measured.

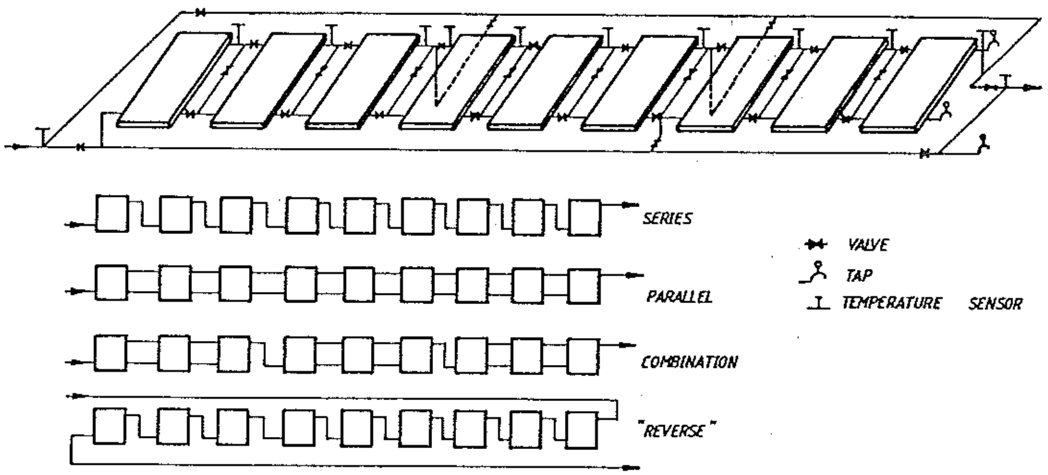

Fig. 2 Collector and valve array

MATHEMATICAL EVALUATION OF THE PERFORMANCE OF AN ARRAY.

According to the Hottel equation (Duffie, 1980) the efficiency of a solar collector can be expressed as:

$$\eta = F' (\tau\alpha)_n - F' U_L \frac{T_{fm} - T_a}{G_T} , \tag{1}$$

$$\eta = F_R (\tau\alpha) - F_R U_L \frac{T_{in} - T_a}{G_T} , \tag{2}$$

or

$$\eta = F_{av} (\tau\alpha)_n - F_{av} U_L \frac{T_{av} - T_a}{G_T} \tag{3}$$

Here, T_{fm} refers to the mean fluid temperature

$$T_{av} = \frac{1}{2} (T_{out} + T_{in}),$$

$$F_R (\tau\alpha)_n = F_{av} (\tau\alpha)_n \frac{\frac{\dot{m}C_p}{A_c}}{\frac{\dot{m}C_p}{A_c} + \frac{F_{av} U_L}{2}} , \tag{4}$$

$$F_R U_L = F_{av} U_L \frac{\frac{\dot{m}C_p}{A_c}}{\frac{\dot{m}C_p}{A_c} + \frac{F_{av} U_L}{2}} \tag{5}$$

Equation (3) is suitable for calculating the useful heat gain over a whole day.

Duffie (1980) also pointed out that test data should be measured at flow rates corresponding to those specified for use in particular applications. If a collector is to be used at a flow rate other than that of the test conditions, an analytical correction to $F_R \ (\tau\alpha)_n$ and $F_R U_L$ should be used. Assume that the only effect of changing the flow rate is to change the temperature gradient in the flow direction and neglect changes in F' due to changes of h_{fi} with the flow rate. Then the ratio, r, by which $F_R U_L$ and $F_R (\tau\alpha)$ are to be corrected is:

$$r = \frac{F_R U_L / \text{use}}{F_R U_L / \text{test}} = \frac{F_R (\tau\alpha)_n / \text{use}}{F_R (\tau\alpha)_n / \text{test}} , \tag{6}$$

$$= \frac{\frac{\dot{m}C_p}{A_c F' U_L} (1 - e^{-A_c F' U_L / \dot{m}C_p}) / _{\text{use}}}{\frac{\dot{m}C_p}{A_c F' U_L} (1 - e^{-A_c F' U_L / \dot{m}C_p}) / _{\text{test}}} \tag{7}$$

However, for a liquid collector, $F'U_L$ is considered to be a constant, so that $F'U_L$ from Equation (8) obtained from test data can also be used in the actual application conditions.

$$F'U_L = \frac{-\dot{m}C_p}{A_c} \ln\left(1 - \frac{F_R U_L A_C}{\dot{m}C_p}\right) \tag{8}$$

These equations (1-8) are essential for calculating the performance of the collector. They can also be used in once-through water heater systems.

ADJUSTMENT OF THE FLOW RATE

For a once-through system consisting of several collectors, the flow rate should be adjusted according to the equation below, in order to keep the outlet temperature fixed (Chinese Solar Energy Society, 1981).

$$\dot{m} = \frac{-A_C F' U_L}{C_p \ln\left(1 - \dfrac{U_L(T_o - T_{in})}{G_T(\tau\alpha) - U_L(T_{in} - T_a)}\right)} \tag{9}$$

Thus the efficiency of the collector can be easily obtained when the radiation, ambient temperature and collector characteristics are known, and an outlet temperature is set.

ANALYSIS OF *n* IDENTICAL COLLECTORS IN SERIES

This kind of array can be treated as a new equivalent collector. Oonk *et. al.* (1979) have shown that the equation below can be used in this situation:

$$F_R(\tau\alpha) = F_{R1}(\tau\alpha)_1 \left(\frac{1-(1-K)^n}{nK}\right), \tag{10}$$

$$F_R U_L = F_{R1} U_{L1} \left[\frac{1-(1-K)^n}{nK}\right]. \tag{11}$$

Here

$$K = \frac{A_{c1} F_{R1} U_{L1}}{\dot{m}C_p}. \tag{12}$$

Duffie (1980) also proposed a method of calculating the performance of series-connected modules of different design or size.

ANALYSIS OF *n* IDENTICAL COLLECTORS IN PARALLEL

Assuming the flow rate in each collector is uniform, the efficiency of the system would be equal to that of one single collector. This assumption was proposed in ASHRAE 95-1981. If the number of collectors is small, this assumption is correct. However, with a large number of collectors, uneven distribution of flow will occur, resulting in a drop in the instantaneous efficiency of the system. Thus the instantaneous efficiency of a parallel system is lower than that of any component collector with the mean flow rate passing through it.

A factor ϕ was calculated by Cawphob (1982) to indicate the drop in efficiency of the system. The definition of ϕ is as follows:

$$\phi = \frac{\Sigma Q_i}{Q_*}. \tag{13}$$

Here, Q_i refers to the useful heat gain of the *i-th* collector with a flow rate different from the mean flow rate, and Q_* refers to the total useful heat gain of n collectors with an assumed uniform flow rate. Equation (13) is then applied again for each collector, yielding:

$$\phi = \frac{\frac{1}{n}\sum_{i=1}^{n} F_{Ri}}{F_{R_*}}.$$

Here, F_{Ri} refers to the heat removal factor of the i-th collector and F_{R_*} refers to the heat removal factor of collectors with the mean system flow rate.

Cawphob (1982) showed that because $F_{R_*} < 0$, the second derivative of F_R versus X $(X = GC_p/F'U_L)$ is less than zero, and therefore ϕ should be less than one. Moreover, the formulation of ϕ by a second order fit in X gives:

$$\phi = [1 - \frac{1}{[2\,X_*^4\;[\exp(\frac{1}{X_*}) - 1]}]\;\frac{1}{n}\sum_{i=1}^{n}(X_i - X_*)^2. \tag{14}$$

Again, X_i and X_* refer to the i-th collector in the real array and a collector with flow rate equal to the mean flow rate. Apply $X = GC_p/F'U_L$ into (14), then ϕ can be given by:

$$\phi = [1 - \frac{1}{2\,(\frac{G_*C_p}{F'U_L})^2\;[\exp(\frac{F'U_L}{G_*C_p}) - 1]}]\,\frac{1}{n}\sum_{i=1}^{n}(\frac{G_i}{G_*} - 1)^2. \tag{15}$$

This analysis is helpful only for understanding the effects of a non-uniform flow rate on the efficiency of a system. However, it is of little use for calculating system performance, because in equation (15) $\sum_{i=1}^{n}(G_i/G_* - 1)^2$ is unknown. This analysis can only be used if the variation of flow in different elements of the array can be evaluated.

COMPARISON OF THE INSTANTANEOUS EFFICIENCY AND PERFORMANCE OF DIFFERENT COLLECTOR ARRAYS.

Analysis of the efficiency of a series array

According to equation (1) (Duffie 1980), the efficiency of the i-th collector in a series connected array of n collectors is:

$$\eta_i = F' [(\tau\alpha) - \frac{U_L}{G_T} (T_{i,fm} - T_a)], \tag{16}$$

and the useful heat gain is:

$$Q_{i,u} = A_c\, G_T F' [(\tau\alpha) - \frac{U_L}{G_T} (T_{i,fm} - T_a)]. \tag{17}$$

Here,

$$T_{i,\, fm} = T_{i,\, in} + K\, (T_{i,out} - T_{i,in}), \tag{18}$$

$$K = \frac{GC_p}{F'U_L} \left(\frac{F'}{F_R} - 1\right) = \frac{1}{1 - \exp\left(\frac{1}{X}\right)} - X, \tag{19}$$

while

$$X = \frac{\dot{m}C_p}{A_c\, F'U_L} = \frac{GC_p}{F'U_L}.$$

It should be pointed out that, in a series-connected array, X and K of all collectors are the same.

Assume:

$$A = e^{-1/x}$$

$$B = 1 - e^{-1/x}$$

$$C = \frac{G_T\, (\tau\alpha)\, (1 - e^{-1/x})}{U_L},$$

one can work out that equation (18) can be written in another form:

$$T_{i,\, out} = A\, T_{i,\, in} + B\, T_a + C,$$

when $i = 1$ to n, and the temperature rise is given by:

$$\Delta T = (A^n - 1)\, (T_{in} + \frac{BT_a + C}{A - 1}),$$

$$\Delta T_i = A^{i-1}\ \Delta T_i,$$

ΔT_i refers to the temperature rise of the first collector.

Furthermore, it can be proved that:

$$\eta_1 = \eta_2 : \ldots : \eta_n = \Delta T_i : \Delta T_2 \ldots : \Delta T_n = 1 : A : A^2 : \ldots : A^{n-1}.$$

Thus, in a series-connected array, the ratio between the temperature rise of two adjacent collectors equals that of the instantaneous efficiency of these two collectors. From the analysis above, it is clear that ratio A is less than one. However, Robertson (1982) pointed out that with n collectors connected in series, the flow rate will increase by n times, i.e. $\dot{m}_n = n_* \dot{m}$. It can also be shown from equations (9) and (7) that the performance of a collector equivalent to such a system is the same as that of the component collector in this system. Thus, in a series array, there are two effects: the efficiency will drop because of the temperature rise, but increase because of the increase in flow rate.

Analysis of the Efficiency of a Parallel Array

As mentioned above, a factor ϕ is introduced to indicate the loss of efficiency in a parallel system. ϕ depends not only on the performance of each collector in the system, but also on the mean flow rate G_* and uniformity of the flow rate as shown in

$$\sum_{i=1}^{n} \left(\frac{G_i}{G_*} - 1\right)^2 .$$

Cawphob *et al.* (1981) calculated a system model for $n = 10$, $G_* = 11$ kg/m²h with G_i of 2,4,6,8,10,12,14,16,18,20 kg/m²h respectively from the first collector to the tenth. In a single glazed flat plate collector with a non-selective surface U_L = 8W/m² °C, ϕ = 0.935. He concluded that, for the same distribution of the flow rate, the relative reduction of the heat produced by a system with a low loss co-efficient resulting from the non-uniform flow rate will be smaller than that for a high loss coefficient collector, while the absolute loss of useful heat gain will be approximately the same.

Figure 3 shows the relationship between ϕ and G_*, $\sum_{i=1}^{n} \left(\frac{G_i}{G_*} - 1\right)^2$.

In order to compare the result of ϕ from equation (15) with the result from our test, n is assumed to equal 9 and the distribution of flow rate was 8:6:4:2:1:3:5:7:9; so that the central collector had the smallest flow rate. This flow distribution was similar to that in the actual system.

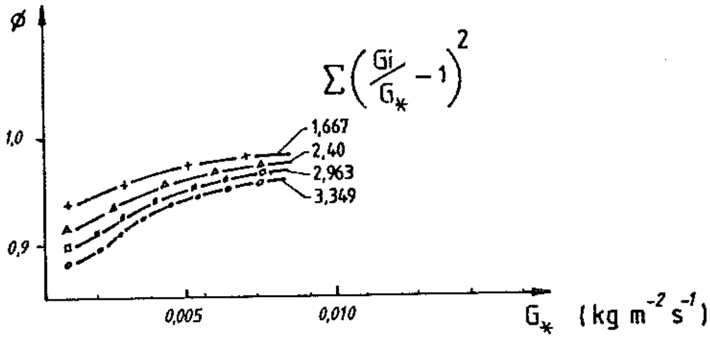

Fig. 3 Relation between ϕ, G_* and $\Sigma\ (G_i/G_* - 1)^2$

The results of parameters from an actual parallel system, as shown in Fig. 4, are listed in Tables 2 to 4. Smaller values of ϕ were for this system from test data, i.e. ϕ_1, ϕ_2 in the tables.

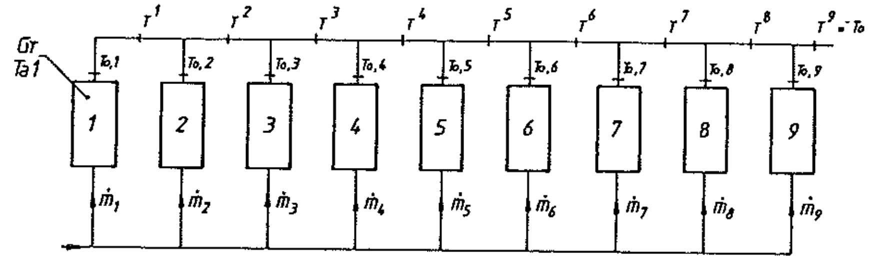

Fig. 4 Parameters in a once through system

Both ϕ_1 and ϕ_2 are smaller than ϕ directly from Equation (15). It is arguable that such a system, either m_* or T_{out} should be maintained as constant and the other would rise slightly, resutling in a decrease of ϕ under the same operating conditions. Besides, Cawphob's method might be applicable only for a pumped recirculation system in which a small flow rate will not occur, whilst in a oncethrough system a small flow rate does occur. Under some radiation and certain ambient conditions (bad weather), m_* will be very small and a situation similar to that presented in Table 4 will occur. In this case, $\phi = 0.8186$, which means that the efficiency will drop 18% compared with a uniform flow rate system.

Table 2. Calculation for a parallel system

($\phi = 0.9667$ from equation (15))

$G_T = 900$ Wm,$^{-2}$ $T_a = 15°C$, $T_{in} = 15°C$, $\Sigma\,(\frac{G_i}{G_*} - 1)^2 = 2.4$

i	1	2	3	4	5	6	7	8	9	Σ
m_i (kgs^{-1})	0.0176	0.0132	0.0088	0.0044	0.0022	0.0066	0.0110	0.0154	0.0198	0.099
$T_{o,\,i}$ (°C)	28.541	32.527	39.799	56.943	76.989	46.230	35.543	30.279	27.157	
$T^{(i)}$ (°C)	28.50	30.20	32.40	24.80	36.80	38.00	37.60	36.20	34.40	34.363
Q_i (kJs^{-1})	.9978	.9689	.9136	.7725	.5711	.8629	.9463	.9852	1.008	8.0261

$m_* = 0.011$ kgs^{-1}	$m_* = 0.01178$ kgs^{-1}
$T_o = 35.543$ °C	$T_o = 34.363$ °C
$Q_{*1} = 8.5155$ kJs^{-1}	$Q_{*2} = 8.5951$ kJs^{-1}
$\phi_1 = 0.9425$	$\phi_2 = 0.9338$

Table 2 to 4 were calculated for

$F'U_L = 8.154$ Wm^{-2}°C^{-1}; $\tau\alpha/U_L = 0.08926$ W^{-1} m^2 °C^{-1}

Table 3. Calculation for a parallel system
(ϕ = 0.9385 from equation (15))

$G_T = 800$ Wm,$^{-2}$ $T_a = 10°$C, $T_{in} = 10°$C, $\Sigma\,(\frac{G_i}{G_*} - 1)^2 = 2.4$

i	1	2	3	4	5	6	7	8	9	Σ
m_i (kgs^{-1})	0.008	0.006	0.004	0.002	0.001	0.003	0.005	0.007	0.009	0.0045
$T_{o,i}$ (°C)	33.831	39.854	49.709	67.336	78.635	57.227	44.119	36.512	31.635	
$T^{(i)}$ (°C)	33.80	36.40	39.40	42.20	43.90	45.60	45.30	43.60	41.20	41.211
Q_i (kJs^{-1})	.7980	.7499	.6649	.4802	.2872	.5933	.7143	.7771	.8152	5.8802

$m_* = 0.005$ kgs^{-1}	$m_* = 0.005653$ kgs^{-1}
$T_o = 44.119$ °C	$T_o = 41.211$°C
$Q_{*,1} = 6.4287$ kJs^{-1}	$Q_{*,2} = 6.6490$ kJs^{-1}
$\phi_1 = 0.9147$	$\phi_2 = 0.8844$

Table 4. Calculation for a parallel system
(ϕ = 0.9138 from equation (15))

$G_T = 700$ Wm,$^{-2}$ $T_a = 10°$C, $T_{in} = 10°$C, $\Sigma\,(\frac{G_i}{G_*} - 1)^2 = 2.4$

i	1	2	3	4	5	6	7	8	9	Σ
m_i (kgs^{-1})	.003472	.002604	.001736	.000868	.000434	.001302	.00217	.003038	.003906	0.01953
$T_{o,i}$ (°C)	47.968	54.536	62.864	71.002	72.447	67.327	58.499	51.035	45.282	
$T^{(i)}$ (°C)	48.00	50.80	53.50	55.20	56.00	57.50	57.60	56.30	54.10	54.136
Q_i (kJs^{-1})	.5518	.4857	.3042	.2217	.1135	.3124	.4405	.5221	.5770	3.6091

$m_* = 0.00217$ kgs^{-1}	$m_* = 0.0026508$ kgs^{-1}
$T_o = 58.499$ °C	$T_o = 54.136$°C
$Q_{*,1} = 3.9659$ kJs^{-1}	$Q_{*,2} = 4.4089$ kJs^{-1}
$\phi_1 = 0.9100$	$\phi_2 = 0.8186$

COMPARISON OF THE THEORETICAL MODEL AND TEST DATA

Test data are listed in Tables 5,6,7. A least squares method is applied to regress the data to equations describing the performance of an array.

The equations for different connection patterns are:

$$\eta = 0.715 - 10.8 \frac{T_{av} - T_a}{G_T} \quad \text{for 9 collectors in series.}$$

$$\eta = 0.715 - 15.3 \frac{T_{av} - T_a}{G_T} \quad \text{for 9 collectors in parallel.}$$

$$\eta = 0.756 - 12.5 \frac{T_{av} - T_a}{G_T} \quad \text{for 3 X iii connection.}$$

Table 5. Test results for 9 collectors in series.

NO.	T_{in} (°C)	T_{out} (°C)	T_a (°C)	G_T (Wm^{-2})	m (kgs^{-1})	Q (kJs^{-1})	$\frac{T_{av} - T_a}{G_T}$ (W^{-1} m^2°C)	η
1	19.05	42.1	25.9	999.0	0.1105	10.480	0.00460	0.6988
2	19.90	46.1	27.9	940.0	0.08033	8.700	0.005426	0.6165
3	21.10	52.2	25.5	850.4	0.06957	9.000	0.01311	0.7049
4	21.40	75.75	29.1	1000.0	0.04031	7.330	0.0210	0.4883
5	25.20	74.65	29.85	1008.5	0.02976	5.850	0.01991	0.3864
6	21.4	45.7	30.55	813.0	0.08632	8.484	0.00369	0.6951
7	20.2	36.4	32.4	690.0	0.1207	7.569	−0.00594	0.7307
8	27.0	81.2	31.6	930.0	0.02552	5.374	0.02422	0.3846
9	27.8	60.9	22.05	701.2	0.03306	5.199	0.0318	0.4938
10	23.0	59.9	24.2	975.0	0.0516	7.608	0.01769	0.5198
11	21.2	53.65	27.0	1008.5	0.08049	10.319	0.01034	0.6816
12	21.1	45.6	23.45	631.0	0.04851	4.551	0.01569	0.4805
13	23.0	61.6	24.2	884.3	0.04457	6.917	0.02047	0.5210
14	26.0	79.7	27.6	988.0	0.02011	4.942	0.02556	0.3332
15	22.5	43.2	28.4	967.6	0.1393	10.807	0.00460	0.7440
16	20.9	39.1	29.5	928.5	0.1578	9.304	−0.00054	0.6675

$$y = 0.7143 - 10.777 \frac{T_{av} - T_a}{G_T}$$

Table 6. Test results for 9 collectors in parallel

NO.	T_{in} (°C)	T_{out} (°C)	T_a (°C)	G_T (Wm^{-2})	m (kgs^{-1})	Q (kJs^{-1})	$\frac{T_{av} - T_a}{G_T}$ (W^{-1} m^2°C)	η
1	21.25	63.85	24.3	959.1	0.03101	5.080	0.01903	0.3528
2	23.15	62.3	25.1	864.3	0.02762	4.385	0.02036	0.3379
3	22.85	52.4	26.15	644.6	0.03828	4.515	0.01780	0.4666
4	20.2	52.0	22.7	648.6	0.04313	5.299	0.02066	0.5442
5	20.4	46.2	24.0	813.9	0.06931	6.812	0.01143	0.5575
6	23.0	69.8	28.0	947.0	0.02916	5.374	0.01943	0.3780
7	17.35	33.80	23.3	487.8	0.08144	4.618	0.004664	0.6306
8	19.8	52.45	20.0	671.8	0.02184	2.683	0.02400	0.2660
9	21.3	51.9	22.65	917.8	0.06531	7.703	0.01520	0.5591
10	19.75	47.4	23.85	990	0.08936	9.410	0.009823	0.6331
11	17.05	32.6	23.15	970.8	0.2089	10.619	−0.003348	0.7287
12	19.0	48.3	26.6	944.9	0.07720	8.431	0.007461	0.5943
13	19.85	41.95	28.3	811.4	0.09901	7.890	0.003204	0.6477

$$y = 0.7145 - 15.27\ \frac{T_{av} - T_a}{G_T}$$

To simulate the array means to find a single collector equivalent to this array. For a series array, equations (7), (10), (11), (12) can be used to solve the problem. For a parallel system, because of flow rate variation between collectors, the performance of any individual collector will not be the

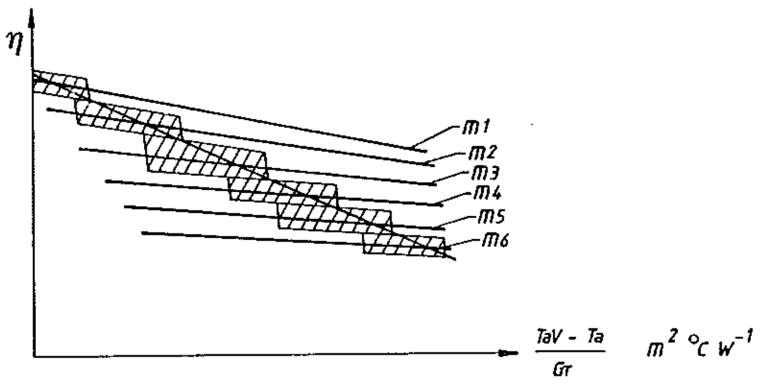

Fig. 5 Set of efficiency curves for different flow rates

Table 7. Test Results for combined array (3 X iii)

NO.	T_{in} (°C)	T_{out} (°C)	T_a (°C)	G_T (Wm^{-2})	m (kgs^{-1})	Q (kJs^{-1})	$\frac{T_{av} - T_a}{G_T}$ ($W^{-1}\ m^2\ °C$)	η
1	20.05	50.4	22.0	972.2	0.07198	8.490	0.01360	0.5817
2	19.05	47.4	22.7	982.2	0.08851	8.999	0.01072	0.6103
3	18.3	43.6	23.2	971.0	0.1075	9.605	0.007982	0.6589
4	18.25	39.6	24.0	933.3	0.1276	9.405	0.005277	0.6713
5	23.1	66.5	24.6	740.3	0.02225	3.858	0.02729	0.3472
6	23.85	74.45	23.9	1010.4	0.03283	6.454	0.02499	0.4255
7	23.75	74.7	24.6	1006.4	0.03206	6.753	0.02447	0.4469
8	26.85	87.7	26.6	953.7	0.02086	5.591	0.03216	0.3905
9	27.75	85.0	28.25	923.6	0.02126	5.223	0.03046	0.3767
10	21.85	66.0	24.7	761.2	0.02300	4.173	0.02526	0.3652
11	23.1	49.6	25.9	580.1	0.05298	5.021	0.01801	0.5765
12	23.15	77.65	26.85	967.6	0.03285	7.450	0.02434	0.5129
13	23.35	73.2	27.6	1072.8	0.04426	8.699	0.01927	0.5402
14	22.0	59.6	27.95	1032.9	0.06656	9.346	0.01244	0.6027
15	20.8	52.3	28.35	957.2	0.08542	10.074	0.008567	0.7010
16	21.3	49.8	29.95	869.7	0.08232	8.496	0.00649	0.6507
17	22.0	39.8	30.2	756.5	0.1355	7.990	0.000925	0.7036

$$y = 0.7560 - 12.533\ \frac{T_{av} - T_a}{G_T}$$

same as the equivalent array collector.

In such a system, the flow rate would affect ϕ: the smaller the flow rate, the smaller ϕ. Therefore, a parallel system has a set of instantaneous efficiency curves. In terms of the HWB model, these are reduced to a set of lines. The working point of a parallel system, in quasi-steady state conditions will jumb from one curve to another rather than move along the equivalent efficiency curve. The working point of an array varies over only a limited range of values of $\Delta T/G_T$. On an equivalent curve for a fixed flow rate, the operating point will move within a limited area around the equivalent curves (Fig. 5).

Since these bands are very narrow, it is possible to use the central line as an equivalent efficiency curve instead of the bands. It would seem reasonable to assume that the working point moves along this line instead of jumping from one band to another. It should be noticed that this equivalent efficiency curve is much steeper than any of the curves for individual collectors. Howe-ever, this does not mean that the heat loss is greater. A similar but simpler analysis can be used with a series or combined array.

The equations from simulating are as follows:

$$\eta = 0.726 - 9.75 \frac{T_{av} - T_a}{G_T} \quad \text{for 9 collectors in series.}$$

$$\eta = 0.713 - 12.6 \frac{T_{av} - T_a}{G_T} \quad \text{for 9 collectors in parallel.}$$

$$\eta = 0.725 - 9.63 \frac{T_{av} - T_a}{G_T} \quad \text{for 3 X iii connection.}$$

These results are also shown in Figs. 6,7 and 8.

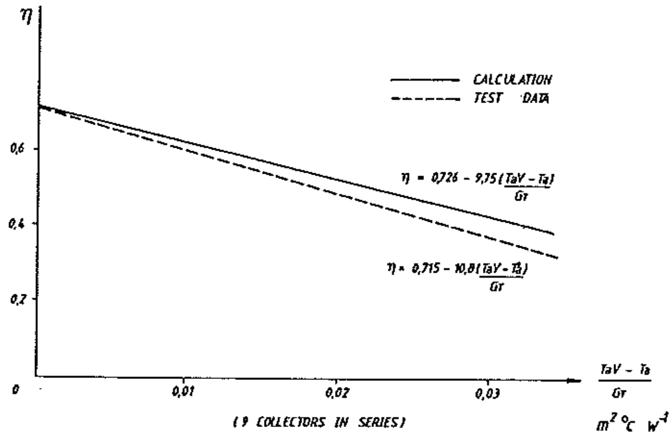

Fig. 6 Comparison of the results from calculation and test data.

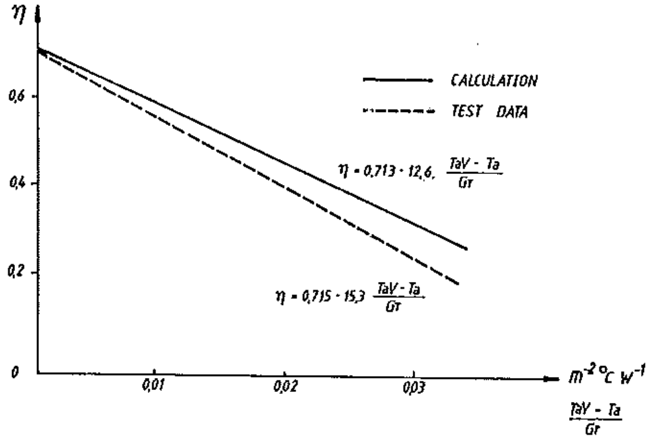

Fig. 7 Comparison of results from calculations and test data (9 collectors in parallel)

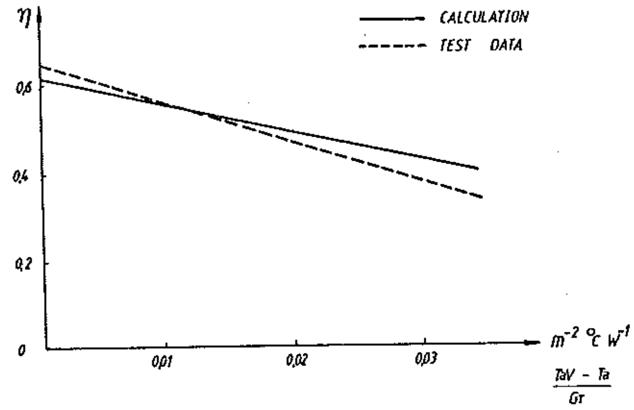

Fig. 8 Comparison of results from calculation and test data (combination 3 X iii)

To summarise, it is possible to use the concept described above to calculate the performance of a system. The difference between the results of this simulation model and test data was less than 10% and usually between 2% and 5%. In order to check these equations for calculating the useful heat gain over a whole day, the results of useful heat gain from tests and calculation are listed in Table 8. The results show that the worst error was less than 10%. It seemed that these equations (1 to 8) could be used to predict the performance of an array for practical purposes.

Table 8. Comparison of useful heat gain from calculation and test data

Connection		9 Collectors in Series			9 Collectors in Parallel			Combination (3 X iii)		
Date of test		3.8 1983	8.8 1983	28.8 1983	8.9 1983	10.8 1983	8.10 1983	22.8 1983	23.8 1983	24.8 1983
GT (kWh) per panel a day		10.786	11.669	10.341	6.598	10.805	7.975	9.041	9.388	5.334
T_{out} (°C)		40.0	40.0	50.0	40.0	40.0	50.0	40.0	40.0	50.0
Calculation	Hot Water (kg)	334.67	393.56	159.44	183.89	319.17	73.79	196.82	224.13	64.27
	Q X 10^3 kJ	25.572	27.643	18.638	13.448	24.461	9.523	18.497	19.700	7.831
Test Data	Hot Water (kg)	345.45	414.72	166.33	202.44	302.07	75.88	229.06	255.79	74.11
	Q X 10^3 kJ	25.369	28.202	19.572	14.036	23.578	10.420	19.116	20.646	8.532
errors	kJ/per panel	203.99	558.50	933.87	587.85	884.17	897.69	619.01	946.81	700.82
	%	0.8	2.0	4.8	4.2	3.8	8.6	3.3	4.6	8.2

CONCLUSION

The concept of the instantaneous efficiency curve can be extrapolated to series-connected or parallel-connected systems, if an equivalent efficiency curve is introduced. However, more information is needed to evaluate the non-uniform flow distribution in parallel systems. A series-connected array is better than a parallel array, because the inherent non-uniform flow distribution in a parallel system will cause a drop in efficiency. The HWB model is only valid when U_L is not a function of temperature, while in a series system, U_L increases with temperature and reaches a level which causes ΔT to fall to zero. There will be an optimum size of a series array, beyond which additional collectors will not work efficiently. In China, 6 collectors is the maximum used in a series array. The instantanous efficiency curves of different arrays are shown in Fig. 9, and useful heat gains are shown in Table 9.

As air blockages can occur, the promision for "air-removal" in a series once-through system should be carefully arranged. Air bleed valves should be located at all the high points of the array. For future investigations, it is suggested that the performance of different quality collectors in a once-through system be evaluated, and the performance of a once-through system connected with flow from top to bottom of the array monitored, since this configuration is easier to construct. The pressure and flow rate distributions between headers and in each collector should be investigated as a matter of some interest.

Table 9. Comparison of different connection arrays

Connection	Test date and Time	T_{out} (°C)	T_a (max) (°C)	T_{in} (°C)	G_T (day) (Whm^{-2})	Q (kJm^{-2})	η (day) %
9 Collectors in Series	3.8 1983 8:30 am – 18:05 pm	40	33.7	18.4 – 26.5	6519	15354.3	65.47
	8.8 1983 8:10 – 18:20	40	34.7	20.1 – 28.1	6996	16893.8	67.13
	29.8 1983 8:00 – 17:23	50	30.8	12.4 – 25.3	6243	11746.2	52.29
9 Collectors in Parallel	9.8 1983 8:00 – 14:00	40	29.2	21.6 – 24.6	3957	8408.8	59.07
	10.8 1983 8:25 – 17:20	40	32.6	20.3 – 23.9	6451	14125.5	60.86
	8.10 1983 8:30 – 16:00	50	22.4	6.8 – 21.5	4794	6243.1	36.20
Combination (3 X iii)	22.8 1983 7:35 – 15:30	40	26.2	12.9 – 19.6	5464	11452.3	58.26
	23.8 1983 8:00 – 16:20	40	26.7	13.3 – 21.0	5628	12369.4	61.09
	24.8 1983 7:50 – 13:20	50	24.9	13.9 – 21.6	3231	5111.7	43.98

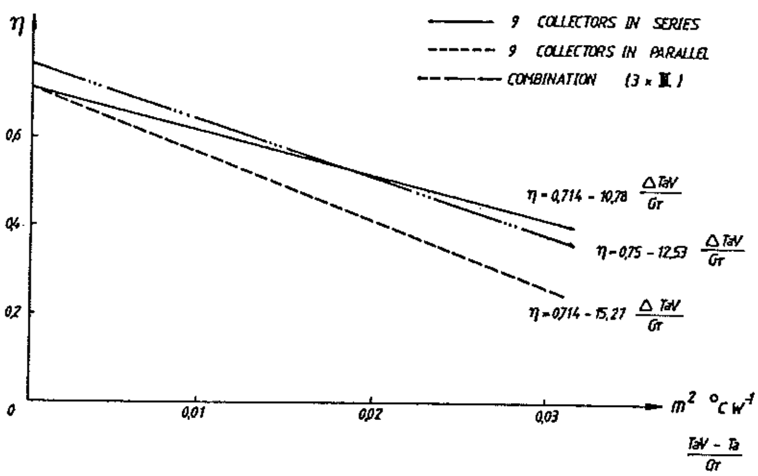

Fig. 9 Efficiency curves for different connection arrays

NOMENCLATURE:

A = area m^2

C_p = specific capacity J/kg °C

F' = efficiency factor

F_R = heat removal factor

G = flow rate per unit collector area $kg/m^2 s$

G_T = radiation W/m^2

m = flow rate kg/s

n = number of collector

T = temperature °C

U_L = heat loss coefficient $W/m^2 °C$

η = efficiency

X = dimensionless factor $X = GC_p/F'U_L$

ϕ = dimensionless factor used in parallel system

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance of Dr. G. Morrison and Mr. W.W.S. Charters who offered valuable suggestions. Thanks are due to Ms. J. Frame for the typing of this article. This work was supported by the GanSu Academic of Science, China.

REFERENCES:

1. ASHRAE 95-1981, Methods of Testing to Determine the Thermal Performance of Solar Domestic Water Heating Systems, *ASHRAE Standard*
2. Cawphob, C.M. et. al. (1981), The Effect of Non-uniform Flow-rate of a Solar Collector System, *Termotexhmka,* No. 1, pp. 24-28.
   New Energy Resources, No. 5, 1982, Peking GenBao translated from Russian.
3. Chinese Solar Energy Society (1981), *Basic Theory of Solar Energy Thermal Processes,* Peking.
4. Duffie J.A. and W.A. Beckman (1980), *Solar Engineering of Thermal Processes,* John Wiley & Sons, New York.
5. Oonk, R.L. *et. al.* (1979), Calculation of Performance of N Collectors in Series from Test Data on Design a Single Collector, *Solar Energy,* Vol. 23.
6. Robertson, H.S. et. al. (1982), Collection of Solar Energy at Specified Output Temperature, *Solar Energy,* Vol. 29, No. 4.
7. Tong, J.I. (University edit.) (1981), *Heat Transfer,* Building publishing house,. Shanghai.
8. Wang Y.F. *et. al.* (1981), Comparing a Once-through System with Thermosyphon Heat System and Calculation, *Acta Energiae Solario Sinica,* Vol. 2, No. 2, *Peking* (Chinese Solar Energy Society Publication).