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ORIGINAL ARTICLES

Thermal Performance of Four Types of Water Heating Flat Plate Solar Collectors for Providing Process Heat for Milk Pasteurisation

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ABSTRACT

Thermal performance tests were carried out on four water heating flat plate solar collectors with the aim to select a suitable one to be used to provide process heat for milk pasteurisation. The collectors included three commercial solar collectors purchased from local shops in Nairobi, Kenya and one prototype collector designed and fabricated by the author. The three commercial solar collectors had effective areas of 1.67, 1.87 and 1.83 m^2 while the self-made collector had an effective area of 1.60 m^2. Thermal performance of the collectors was determined in terms of the Hottel-Whillier-Bliss equation, with $F_R(\tau\alpha)_e$ and F_RU_L indicating how energy is absorbed and lost from the collector, respectively. The $F_R(\tau\alpha)_e$ values were 0.76, 0.75, 0.73, and 0.82, respectively, for the commercial collectors and the self-made collector. The F_RU_L values were 8.33, 12.01, 9.80 and 13.77 $W.m^{-2}.C^{-1}$, respectively. The instantaneous efficiencies for the four solar collectors ranged from 12 to 87%. The solar collector with the lowest F_RU_L value had a special (black chrome) selective absorber surface and was also the most cost effective collector for delivering temperatures of about 80°C. This collector is the most suitable for medium temperature applications such as provision of hot water for milk pasteurisation.

Key words: thermal performance, flat-plate solar collectors

Nomenclature:

A	Effective area of solar collector absorber (m^2)
F_R	Collector heat removal factor (dimensionless)
I	Insolation in plane of solar collector (W/m^2)
$\dot{m}$	water flow rate through solar collector (kg/s)
Q_u	Rate of useful heat output from solar collector (W)
T_a	Ambient air dry bulb temperature (°C)
T_i	Inlet water temperature in a solar collector (°C)
T_o	Outlet water temperature in a solar collector (°C)
U_L	Heat loss coefficient of solar collector ($W/m^2.°C$)
v	Wind speed (m/s)
α	Absorbance of the collector plate (dimesionless)
$(\tau\alpha)_e$	Effective transmittance-absorbance product for solar collector (dimensionless)
η	Efficiency of solar collector (%)
τ	Transmissivity of the transparent cover of solar collector (dimensionless)
λ	Geographic latitude

Introduction

Milk marketing is an important income earning opportunity for people in the arid and semi arid lands (ASALs) of Kenya. To minimise losses along the marketing chain, traders boil milk using firewood, especially when transport to the market is unavailable. This, however, places intense pressure on woody resources on the already fragile environment. Therefore, alternative cheap and renewable energy technologies such as solar energy should be provided to small scale farmers and traders who are involved in milk marketing. Kenya has enormous amounts of solar energy resource particularly in the ASALs—where the monthly average of global

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solar radiation varies from 13.3 to 30.6 $MJ.m^{-2}.day^{-1}$ (Kenya Meteorological Department, Solar radiation records 2000-2009, unpublished) and, therefore, solar energy seems to be a viable alternative to firewood for heating milk.

In any solar energy system, the most important component is the collector, which needs to be selected very carefully. Flat plate solar collectors are the most common collectors used for delivery temperatures up to 100°C (Duffie and Beckman, 2006). One measure of the quality of a flat plate collector is its thermal efficiency (η), defined as the proportion of the solar energy incident on the collector that is transferred to the water flowing through the collector. It is given by the Hottel-Whillier-Bliss equation (Duffie and Beckman, 2006):

$$\eta = F_R(\tau\alpha)_e - F_R U_L (T_i - T_a)/I \quad (1)$$

where, F_R is the collector heat removal factor, $(\tau\alpha)_e$ is the effective transmittance-absorbance product for the solar collector, U_L is the heat loss coefficient of collector ($W.m^{-2}.°C^{-1}$), T_i is the inlet water temperature in a solar collector (°C), T_a is the ambient air temperature (°C), and I is the insolation in plane of the collector ($W.m^{-2}$)

Therefore, to test the thermal performance of flat plate solar collectors, it is necessary to determine efficiency (η) as a function of $(T_i - T_a)/I$. Determining the thermal performance of solar collectors helps to select a suitable collector for a given duty and provides information necessary in designing a solar energy system (Duffie and Beckman 2006). This is especially necessary since a wide range of solar collectors is produced by numerous manufacturers all over the world. Therefore, it is very important to choose the right collector for each application in order to optimise the performance of the whole system, the energy savings and the finance payback. This study, therefore, aimed to select a suitable solar collector, based on thermal performance, to be used to provide process heat for batch pasteurisation of milk in the ASALs of Kenya. To our knowledge, no previous work has examined this before. For this aim, four solar collectors were tested—one prototype collector designed and fabricated by the author and three commercial solar collectors purchased from local shops in Nairobi, Kenya.

Materials and Methods

Solar collectors:

Solar collector A:

This was a self-made flat-plate solar collector fabricated by the authors. The collector had a 2.1 m^2 gross area while the effective area measured 1.6 m^2 (the effective area being the absorber cross-sectional area exposed to solar radiation). The sizing of the collector was based on information from Okoth and Williams (1986) and the potential to provide process water to pasteurise at least 40 litres of milk as a batch. Materials used were those that could be readily available in the ASALs where the collector was intended to be used. The absorber was made from a standard sheet of galvanised steel (gauge 24), and painted black by matt black paint. The absorber plate was enclosed in a galvanised steel tray and wooden casing with 50 mm thick bottom and side cotton wool insulation. The collector had ten risers of 19 mm inner diameter galvanised iron tubes, which were bonded tightly to the absorber plate so that good thermal contact was maintained between the absorber plate and the riser tubes. The spacing between each riser was 10 cm. One clear window glass of 4 mm thickness was used for the transparent cover.

Solar collector B:

This was a commercial solar collector imported from South Africa and assembled by Go-Solar Ltd, Nairobi, Kenya. The gross and effective area measured 1.82 m^2 and 1.67 m^2, respectively. The absorber was made of a copper sheet to which was soldered ten 12.7 mm nominal diameter copper tubes. The surface was treated with a selective coating (black chrome). The glazing was a special low iron glass sheet (5 mm thick) treated on the outer surface to minimise transmission of long-wave infrared radiation. The rear and side insulation were 25 mm and 10 mm thick fibre glass, respectively. The casing material was 24 gauge galvanised steel sheet, with a layered assembly of rubber and metallic sheet compacted by a sealing gasket.

Solar collector C:

This was a commercial non-selective solar collector assembled by Solar Gent Ltd., Nairobi, Kenya. The gross and effective area measured 1.98 m^2 and 1.83 m^2, respectively. The absorber was made of aluminium sheet to which was soldered six 11 mm nominal diameter copper tubes, separated by centre-to-centre distance of

15 cm. The glazing was clear window glass (4 mm thick). The casing was 24 gauge riveted galvanised steel sheet. Glass wool and cork sheet were used as insulation, with the rear and side insulation being 25 mm and 10 mm thick, respectively.

Solar collector D:

This was an industrial non-selective collector assembled by Davis and Shirtliff, Nairobi, Kenya. The transparent cover was clear glass sheet (5 mm thick). The gross and effective areas were 1.96 m^2 and 1.87 m^2, respectively. The absorber was made of galvanised steel sheet and the insulation was glass wool.

Experimentation:

The system was installed at the Kenya Agricultural Research Institute (KARI), National Arid Lands Research Centre, Marsabit (37.97°E, 2.32°N, altitude 1219 m). A schematic diagram of the test system is shown in Fig. 1. It is a modification of the system used by Okoth and Williams (1986), which is arguably the first method (with published results) of solar collector testing in Kenya. A by-pass was provided around the pump so that the mass flow rate could be adjusted to the desired value. Similarly, the electric immersion heaters provided a means for adjusting and controlling the inlet water temperature to the collector. The four solar collectors were tested one at a time. The collector was tilted at 17° from the horizontal, facing the equator. Measurements were taken only when there was uninterrupted period of sunshine. Measurements were not taken when the insolation was less than 600 W. m^{-2} and/or the wind speed was greater than 6 m/s (Duffie and Beckman, 2006). All measurements were taken between 10.00 and 16.00 hours standard local time.

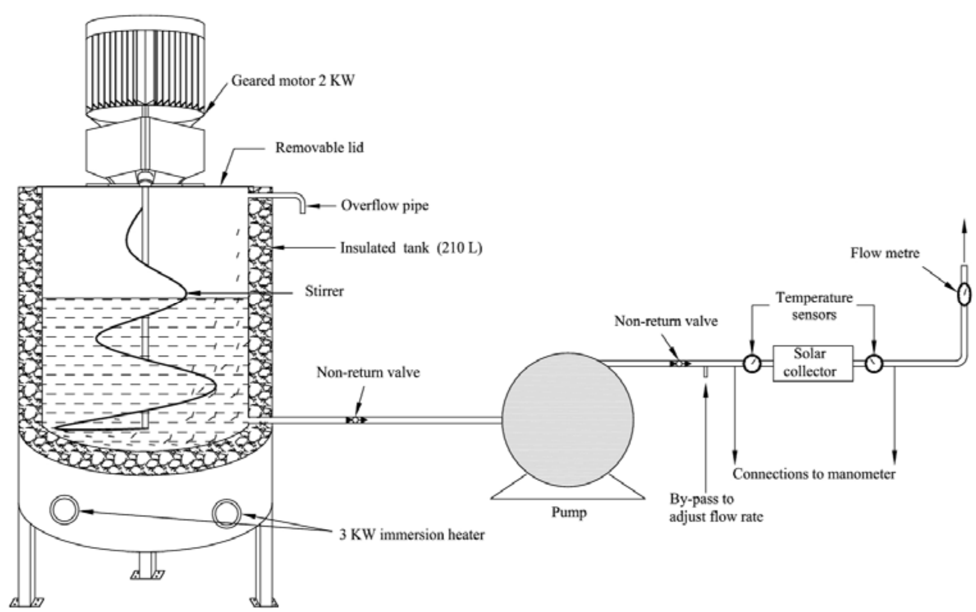

Fig. 1: Schematic diagram of the solar collector testing unit

Water was maintained at a desired temperature in the insulated tank and pumped through the solar collector at a constant flow rate (0.02 kg.s^{-1} per m^2 of effective collector area). The first set of measurements was taken after 30 minutes of operation at the specified inlet water temperature and mass flow rate. Care was, however, taken to ensure the inlet water temperature was kept at a value higher than the ambient temperature to allow heat exchange between the collector and its surrounding. Subsequent measurements were made 15 minutes after changing the inlet water temperature to a new value. Measurements taken included the flow rate of water ($\dot{m}$), inlet water temperature (T_i), outlet water temperature (T_o), ambient temperature (T_a), insulation in the plane of the collector (I) and wind speed (v). The experiment was repeated several times for each solar collector using different values of the inlet water temperature (ranging from 23 to 69°C).

Water flow rate was measured using a rotameter (G. A. Platon Ltd., Basingstoke, U.K.). Water temperatures were measured using iron-constantan K-Type thermocouple thermometer (type HI 9043, Hanna Instruments, Padova, Italy). To avoid perturbing fluid flow, probes of low dimensions made of diode 1N4148 with silicon of 1.6 mm diameter, of ±0.5°C precision, were used. The probes were mounted at the collector inlet and outlet. Ambient temperature was measured using a digital thermometer (0°C to 60°C, Model No. ETH529, Brannan Thermometers, Cleator Moor, Cumbria, England). Insolation in the plane of the collector was measured by pyranometer (Kipp and Zonen, Delft, Netherlands) and wind speed by cup-and-vane anemometer, which indicated wind speed values in the range 0 to 30 $m.s^{-1}$ (full scale = 10 divisions; 1 division = 3 $m.s^{-1}$). The experiment was repeated several times for each solar collector using different values of the inlet water temperature (ranging from 23 to 69°C).

Statistical analysis:

Data were analysed in MS-Excel 2003 for Windows. A first-order least squares regression analysis was applied to all the measured data points to obtain efficiency curves. For analysis of parallelism, simple linear regression with groups was carried out in GenStat (2007) to compare the parameters of the four regression lines.

Results and Discussion

Experimental data showing thermal performance of the solar collectors A, B, C and D are shown in Tables 1 to 4. Efficiency curves for the collectors are shown in Figs. 2 to 5. Efficiency in the tables and figures is expressed as a percentage whereas it is fractional in Eq. (1). The scatter of the data around the straight line was mainly attributed to variations in ambient air temperature, wind speed and the dependence of U_L on the absorber temperature. In addition, the variations of the relative proportions of beam, diffuse and ground reflective components of solar radiation are participating in the data scattering (Duffie and Beckman, 2006; Kalogirou, 2004). However, it is acceptable that the collectors are characterised by the Hottel-Whillier-Bliss equation with line intercept $F_R(\tau\alpha)_e$ and slope $-F_RU_L$.

Table 1: Experimental data showing thermal performance of solar collector A

Expt.* No.	Water inlet temp*, T_i (°C)	Water outlet temp, T_o (°C)	Ambient temp, T_a (°C)	Insolation ($W.m^{-2}$)	Wind speed ($m.s^{-1}$)	Water flow rate (kg. s^{-1})	$(T_i-T_a)/I$ (°C.$m^2.W^{-1}$)	Efficiency, η (%)
1	23.0	33.5	22.5	801.3	5.3	0.024	0.000624	82.6
2	23.6	36.3	22.6	950.3	4.8	0.024	0.00105	84.2
3	24.5	35.8	23.1	914.3	2.8	0.024	0.00153	77.9
4	27.0	39.0	24.5	873.1	3.6	0.024	0.00286	86.6
5	31.8	40.0	23.9	804.5	2.1	0.024	0.00982	64.2
6	36.7	42.0	24.5	697.7	2.9	0.024	0.0175	47.9
7	41.0	47.4	26.5	750.3	1.1	0.024	0.0193	53.7
8	45.4	50.7	25.7	715.2	1.8	0.024	0.0275	46.7
9	50.3	55.9	27.6	863.1	2.1	0.024	0.0263	40.9
10	57.0	61.5	27.9	815.3	2.9	0.024	0.0357	34.8
11	60.5	64.5	28.5	790.7	1.7	0.024	0.0405	31.9
Mean	38.3	46.1	25.2	816.0	2.8	0.024	0.0166	59.2
Min	23.0	33.5	22.5	697.7	1.1	0.024	0.000624	31.9
Max	60.5	64.5	28.5	950.3	6.3	0.024	0.0405	86.6

*Expt. No. =Experiment number, temp = temperature

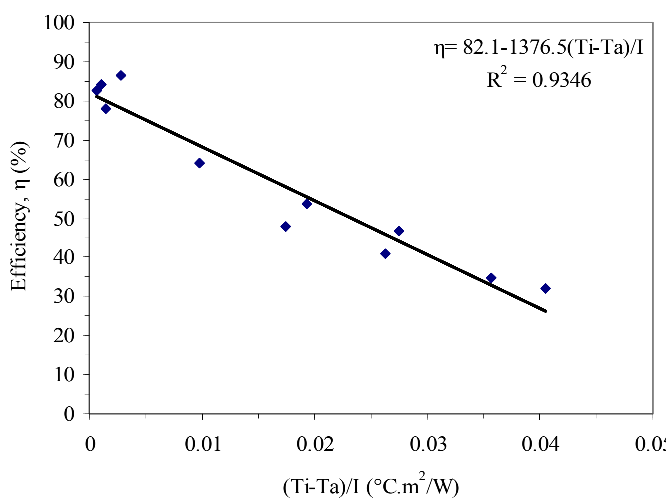

Fig. 2: Efficiency curve for collector A

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Table 2: Experimental data showing thermal performance of solar collector B

Expt.* No.	Water inlet temp*, T_i (°C)	Water outlet temp, T_o (°C)	Ambient temp., T_a (°C)	Insolation ($W.m^{-2}$)	Wind speed ($m.s^{-1}$)	Water flow rate ($kg. s^{-1}$)	$(T_i\text{-}T_a)/I$ ($°C.m^2.W^{-1}$)	Efficiency, η (%)
1	23.9	31.8	20.3	809.5	2.3	0.029	0.00445	71.2
2	33.3	40.3	20.4	784.3	2.1	0.029	0.0164	65.1
3	49.9	55.4	24.7	841.3	3.6	0.029	0.0300	47.7
4	65.9	69.8	23.2	814.4	3.3	0.029	0.0524	34.9
5	68.9	72.4	24.7	882.5	3.6	0.029	0.0501	28.9
6	63.7	68.7	25.1	819.3	4.5	0.029	0.0471	44.5
7	61.4	66.0	25.7	815.6	4.8	0.029	0.0438	41.1
8	57.9	62.2	25.4	808.9	3.9	0.029	0.0402	38.8
9	54.3	59.6	24.3	869.4	4.2	0.029	0.0345	44.5
10	51.0	56.8	25.1	804.4	4.3	0.029	0.0322	52.6
11	64.3	67.9	27.2	794.4	4.5	0.029	0.0467	33.1
Mean	54.0	59.2	24.2	822.2	3.7	0.029	0.0362	45.7
Min	23.9	31.8	20.3	784.3	2.1	0.029	0.00445	28.9
Max	68.9	72.4	27.2	882.5	4.8	0.029	0.0524	71.2

*Expt. No. =Experiment number, temp = temperature

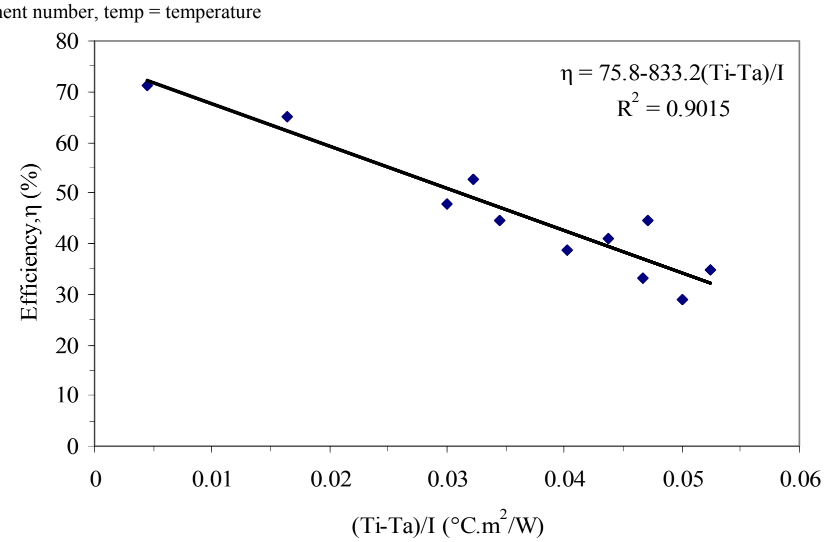

Fig. 3: Efficiency curve for collector B

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Table 3: Experimental data showing thermal performance of solar collector C

Expt.* No.	Water inlet temp*, T_i (°C)	Water outlet temp, T_o (°C)	Ambient Temp, T_a (°C)	Insolation ($W.m^{-2}$)	Wind speed ($m.s^{-1}$)	Water flow rate ($kg. s^{-1}$)	$(T_i-T_a)/I$ ($°C.m^2.W^{-1}$)	Efficiency, η (%)
1	24.8	34.6	23.9	829.3	4.3	0.026	0.00114	70.5
2	33.1	41.3	24.8	794.4	4.8	0.026	0.0104	61.6
3	35.1	45.3	24.8	819.5	2.8	0.026	0.0126	74.3
4	38.2	45.7	24.6	806.9	3.6	0.026	0.0169	55.5
5	39.4	45.7	25.1	814.4	3.7	0.026	0.0176	46.2
6	42.3	51.2	24.3	950.6	2.1	0.026	0.0189	55.9
7	45.2	50.2	25.3	805.4	2.9	0.026	0.0247	37.0
8	43.3	50.5	24.9	869.4	3.9	0.026	0.0212	49.4
9	47.0	54.0	25.4	882.5	4.2	0.026	0.0245	47.3
10	49.9	55.9	25.4	822.9	4.3	0.026	0.0298	43.5
11	52.0	56.2	25.6	794.4	4.5	0.026	0.0332	31.5
12	53.0	57.4	26.1	804.4	3.7	0.026	0.0334	32.6
13	57.8	62.6	26.7	825.8	2.1	0.026	0.0377	34.7
14	61.2	64.1	27.0	820.1	2.1	0.026	0.0417	21.1
15	64.2	67.3	27.0	804.4	2.9	0.026	0.0462	23.0
16	67.6	69.2	26.8	774.4	3.9	0.026	0.0527	12.3
Mean	47.1	53.2	25.5	823.7	3.5	0.026	0.0264	43.5
Min	24.8	34.6	23.9	774.4	2.1	0.026	0.00114	12.3
Max	67.6	69.2	27.0	950.6	4.8	0.026	0.0527	74.3

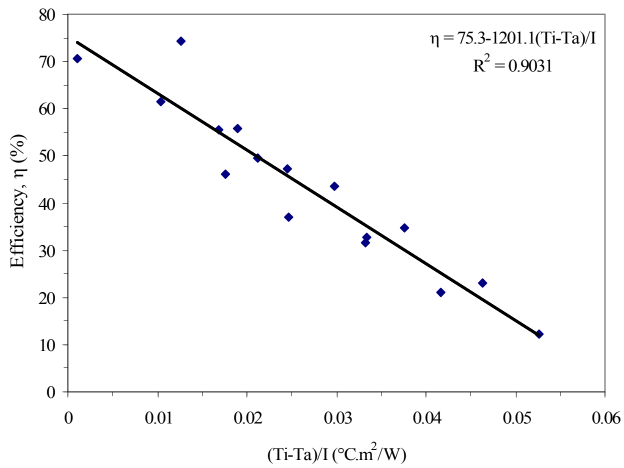

Fig. 4: Efficiency curve for collector C

Table 4: Experimental data showing thermal performance of solar collector D

Expt.* No.	Water inlet temp*, T_i (°C)	Water outlet temp, T_o (°C)	Ambient Temp, T_a (°C)	Insolation ($W.m^{-2}$)	Wind speed ($m.s^{-1}$)	Water flow rate ($kg. s^{-1}$)	$(T_i-T_a)/I$ ($°C.m^2.W^{-1}$)	Efficiency, η (%)
1	25.1	37.1	22.8	739.2	5.4	0.019	0.00311	68.5
2	27.8	39.1	24.2	698.3	5.5	0.019	0.00516	68.3
3	32.2	44.1	23.3	836.9	5.1	0.019	0.0106	60.0
4	38.5	47.0	22.9	681.3	3.8	0.019	0.0229	52.7
5	43.2	51.1	22.7	764.4	2.9	0.019	0.0268	43.6
6	48.6	59.3	23.6	872.5	5.9	0.019	0.0287	51.8
7	53.0	58.5	24.0	706.3	6.0	0.019	0.0411	32.9
8	46.7	55.3	24.5	765.6	6.0	0.019	0.0290	47.4
9	54.0	59.5	24.7	758.9	5.9	0.019	0.0386	30.6
10	57.5	62.5	24.6	807.0	5.8	0.019	0.0408	26.2
11	61.5	65.2	24.9	724.4	5.4	0.019	0.0505	21.6
12	59.3	64.2	26.9	734.4	5.1	0.019	0.0441	28.2
13	60.0	65.6	27.1	724.4	5.7	0.019	0.0454	32.6
14	62.1	66.6	25.1	734.4	5.5	0.019	0.0504	25.9
Mean	47.8	55.4	24.4	753.4	5.6	0.019	0.0312	42.2
Min	25.1	37.1	22.7	681.3	4.8	0.019	0.00311	21.6
Max	62.1	66.6	27.1	872.5	6.0	0.019	0.0505	68.5

*Expt. No. =Experiment number, temp = temperature

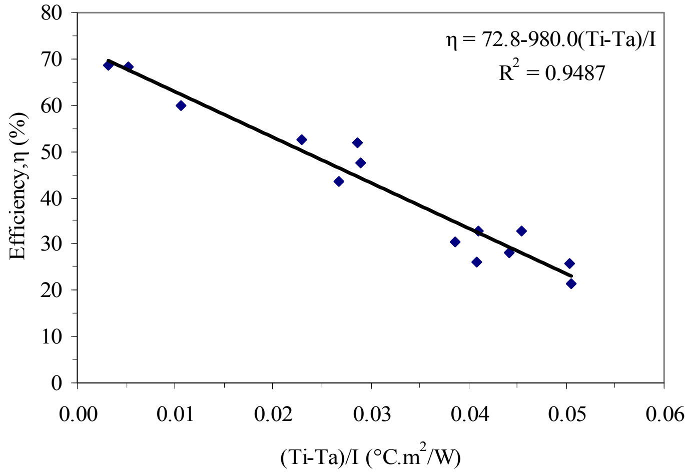

Fig. 5: Efficiency curve for collector D

The $F_R(\tau\alpha)_e$ values for the collectors A, B, C and D were 0.82, 0.76, 0.75 and 0.73, respectively. The F_RU_L values were 13.77, 8.33, 12.01 and 9.80 W.m^{-2}.K^{-1}, respectively. Similar values for solar collector parameters were reported for solar collectors in Kenya (Okoth and Williams, 1986) and Coté d'Ivoire (Andoh *et al*., 2007). Solar collector A had the highest $F_R(\tau\alpha)_e$ mainly because the clear glass cover had a much higher transmittance, with regard to incoming shortwave solar radiation, than the glass covers for the other collectors. Solar collector A also had the highest value of F_RU_L not only because it had a non-selective absorber surface, but also because the cotton wool insulation had the highest heat losses from the sides of the collector. Cotton wool was used because it was the most readily available and affordable insulation material for use in the ASALs. Solar collector B had the lowest F_RU_L value mainly because it had a selective absorber surface which resulted in much less long-wave thermal radiation being emitted by the absorber, in comparison with the other solar collectors. This collector also had a special glass glazing (and not clear window glass of the other collectors) which minimised transmission of long-wave thermal radiation emitted from the absorber surface. The casing was also air tight with rubber gaskets all round, resulting in an enhancement of the thermal efficiency of the collector by creating a greenhouse effect.

From the efficiency curves in Figs. 2 to 5 it can be observed that the efficiency of the flat plate collectors is higher in the case of low values of reduced temperature difference, $(T_i - T_a)/I$; the opposite occurs when the reduced temperature difference is higher than 0.035 °C.m^2.W^{-1}. This result is expected for flat plate collectors: the efficiency is higher because of the better value of zero loss efficiency; when increasing the reduced temperature difference, efficiency is penalised by the higher heat loss coefficient (Zambolin and Del Col, 2010). The comparative thermal performance of the four collectors is shown in Fig. 6.

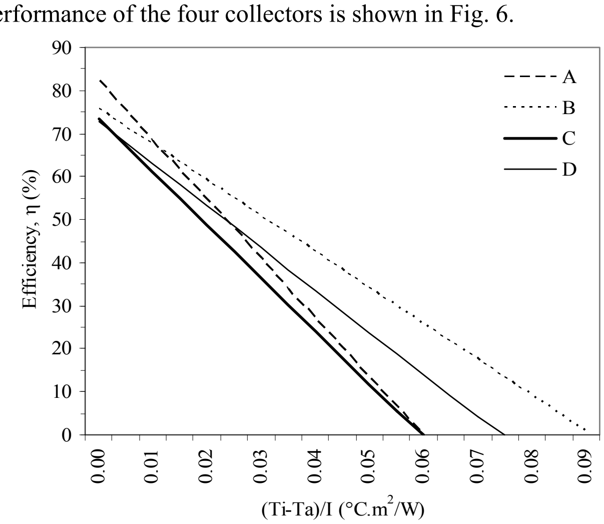

Fig. 6: Comparison of the thermal performances of solar collectors A, B, C and D

The efficiency curves are close at low values of the reduced temperature parameter values $F_R(\tau\alpha)_e$ and F_RU_L. As these parameters increase, the curves diverge because the efficiency becomes more dependent on F_RU_L

and decreases with the increase of heat loss. These results corroborate the findings of Andoh *et al*. (2007) in Coté d'Ivoire. Statistical analysis showed that collector A and C were not significantly different from each other, whereas all the other combinations of collectors were significantly different (t-statistic, $p \leq 0.05$) from each other (Table 5).

It is clear that based on efficiency alone the choice of the most suitable solar collector depends on the operating temperature. Given the efficiency curve for a solar collector, knowledge of the insolation, ambient temperature and inlet water temperature enables one to determine the instantaneous efficiency of the collector (Duffie and Beckman, 2006). For example, the average insolation and ambient temperature at KARI-Marsabit campus between 10.00 and 16.00 hours on 13th July 2010 were 783.7 $W.m^{-2}$ and 23.8°C, respectively. Table 6 shows the predicted (calculated) performance of the four solar collectors. The theoretical maximum temperatures which could be reached by collectors A, B, C and D were 70.6, 95.1, 72.9 and 82.0°C, respectively. Solar collector B could still operate at an efficiency of 5.4% at an inlet temperature of 90°C, and is thus the most suitable to provide process heat for milk pasteurisation. In practice, however, it may not be economical to seek to achieve these theoretical maximum temperatures. One would, for instance, design a solar water heating system such that each solar collector operates at no less than 15% efficiency. Even with this restriction, solar collector B could attain maximum temperatures above 80°C on 13th July 2010.

Knowledge of the maximum temperature attainable by a solar collector is useful when selecting a solar collector for a specified temperature application. It is clear that solar collector B is the most suitable collector for provision of process heat for batch pasteurisation of milk (63°C for 30 min).

Besides efficiency, cost considerations are also important in selecting the most suitable solar collector. Capital costs for solar collectors A, B, C and D were USD 420, 427, 467 and 560 per m^2 of effective collector area, respectively. Assuming that the storage tank is filled with water at 25°C in the morning, and that heating continues until the water temperature reaches 60°C, the average collector efficiencies calculated from Table 6 are 18.5, 37.3, 19.8 and 27.5%, respectively. Solar collector B is thus still the most efficient collector while collector A is the least efficient. The cost per unit area to efficiency ratios for the solar collectors A, B, C and D were, therefore, 22.7, 11.4, 23.6 and 20.4. Solar collector B thus emerges as the most cost effective collector. The maintenance costs for the collectors in the ASALs include regular cleaning of the glass cover with damp cloth to remove dust as it is very dusty in the ASALs where the solar collectors are to be used for pasteurising milk. Also, normal clear window glass used as glazing for the collectors A, C and D is prone to breakage due to handling in the rough terrain of the ASALs (especially during installation) and expansion and contraction due to heating from the solar radiation and may have to be replaced regularly.

Even though the performance of the self-made collector compared favourably with collector C in terms of $F_R U_L$ and efficiency, this performance was not adequate to provide demand temperature for milk pasteurisation. This means that, whereas a locally fabricated collector may be cheaper, its efficiency may not be adequate for the required demand temperature. This finding confirms the results of Okoth and Williams (1986) who reported the results of efficiency tests on four types of water heating flat plate collectors performed in Nairobi, Kenya using a common test procedure and found the self made collector to be the least efficient in terms of thermal performance. Therefore, to design solar water heating systems to meet required demand hot water temperature it is better to purchase a commercial solar collector of known performance efficiency and integrate it with the other components that can be locally fabricated.

Conclusions:

Based on thermal performance solar collector B, a single glazed collector with a black chrome selective surface and a special glass cover was the best performing (and most cost effective) flat plate collector for delivery temperatures of about 80°C. This collector is the most suitable for medium temperature applications such as provision of hot water for milk pasteurisation (63°C for 30 min). It can be used to provide process water in a low cost flat-plate batch solar milk pasteuriser for arid pastoral areas which have abundant solar energy resource, but scarce conventional sources of energy, and where milk marketing is an important income earning opportunity.

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