

Optimiranje ravnega sončnega sprejemnika z nepremičnim zrcalom

The Optimization of a Solar Collector of the Flat-Thin Box Type with a Fixed Reflector

Ha Dang Trung - Nguyen Quan

Pri raziskavi novega tipa sončnega sprejemnika je bilo uporabljeno zrcalo nepremičnega tipa. Sprejemnik in zrcalo sta utrjena, tako je količina absorbirane sončne energije odvisna predvsem od kota sončnih žarkov ter razporeditve sprejemnik – zrcalo. Visoko temperaturo vode in največje absorbirano sevanje tako dosežemo z optimalno postavitvijo sprejemnika in zrcala. Raziskave so pokazale, da je primerno razmerje izmer od 1,7 do 3 (da dobimo od 33% do 38% več neposrednega sevanja). Prvotni rezultati pri preskusu ravnega sprejemnika sončnega sevanja, ki je imel površino 3,9 m² in zrcalo enake površine, so bili spodbudni.

Ta model sončnega sprejemnika je preprostejši in bolj učinkovit v območjih zmernega sončnega sevanja in uporaben za absorpcijski hladilni krog.

© 2000 Strojniški vestnik. Vse pravice pridržane.

(Ključne besede: sprejemniki sončni, absorpcija energije, optimiranje, preskušanje)

A new design of solar collector has been investigated which uses a reflector of the fixed type. Both collector and mirror are of the non-tracking type, so the absorbed solar energy depends on the incident angle of the solar beam and the collector-mirror arrangement. A high water temperature and a maximum in the absorbed radiation can be reached by selecting an optimal dimension ratio for the collector and reflector. The research has shown that reasonable dimension ratio of 1.7 to 3 can result in 33% to 38% more direct radiation. A flat-thin box type collector of 3.9 m² with a mirror of the same area has been tested and some initial results look promising.

This model of solar collector is simpler and more efficient in regions of moderate solar radiation and useful for the absorption-refrigeration cycle.

© 2000 Journal of Mechanical Engineering. All rights reserved.

(Keywords: solar collector, absorbed energy, optimization, testing)

0 UVOD

Uporaba kombinacije sprejemnik – zrcalo je bila omenjena v nekaterih projektih in raziskavah. Za pridobitev čim več sončnega sevanja je pomembno razmerje izmer zrcala in sprejemnika ter površina sprejemnika. Za okrogel ploščat sprejemnik brez zrcala ali zgoščevalnika premičnega tipa je absorbirana sončna energija odvisna od površine sprejemnika. To pomeni, da imajo različni sprejemniki enake površine enako možnost absorpcije, čeprav se njihova razmerja izmer razlikujejo. Za kombinacijo sprejemnik – zrcalo nepremičnega tipa pa je vse skupaj bolj zapleteno. Absorbirana sončna energija, ki vključuje odbojno sevanje, je odvisna od razmerja izmer in spremembe kota sončnih žarkov.

0 INTRODUCTION

Using a collector-reflector combination as a solar collector has been mentioned in some projects and researches, but the dimensional relationship of the reflector and collector is often based on the collector's area to obtain the determined solar radiation and taken qualitatively. For the flat-plate collector without reflector or concentration collector of the tracking type, absorbed solar energy depends on the collector area, not on its dimension ratio. This means the different collectors of the same area have the same capacity while their dimension ratios are not the same. But for the collector-reflector combination of the fixed type, the problem is more complicated. Absorbed solar energy, which includes the reflection radiation, depends on the dimensional relationship with the change of incident angle of the solar beam.

Pri optimiranju sprejemnikov sončne energije naletimo na problem, kako narediti kombinacijo sprejemnik – zrcalo preprosto za izdelovanje, uporabo in vzdrževanje, cenovno ugodno in energijsko učinkovito. Za izpolnitev teh pogojev je bil oblikovan in testiran model sončnega sprejemnika z nepremičnim zrcalom.

For the optimization of a solar collector, the problem is how to make the solar collector-reflector combination simple to manufacture, convenient to operate and maintain, cheap to produce while offering improved energy efficiency. To meet these requirements, a model of a solar collector with a fixed-type reflection mirror has been designed and tested.

1 ODVISNOST ABSORBIRANE ENERGIJE OD IZMER SPREJEMNIK – ZRCALO

1 DEPENDANCE OF ABSORBED ENERGY ON THE COLLECTOR-MIRROR DIMENSIONS

Absorbirano energijo, ki jo sprejme okrogli ploščati sprejemnik z nepremičnim zrcalom določimo [1] iz obrazca:

Useful absorbed energy for a flat-plate collector with a fixed type mirror [1] is defined by:

$$dQ_u = A_c [F_r (\tau\alpha) (I_T + f_A I_R)] d\omega \quad (1)$$

kjer je:

where:

- Q_u – absorbirana energija v J
- A_c – površina ravnega okroglega sprejemnika v m^2
- F_R – količnik prenosa toplote
- $(\tau\alpha)$ – zmnožek transmisivnosti in absorptivnosti
- I_T – celotno sevanje v W/m^2
- I_R – odbojno sevanje ogledala v W/m^2
- ω – časovni korak, ki ustreza sončnemu urnemu kotu v s
- $f_A = A_R/A_C$ – razmerje površin
- A_R – površina sprejemnika, ki zbira odbojno sevanje ogledala v m^2

- Q_u – useful absorbed energy, J
- A_C – surface area of the flat-plate collector, m^2
- F_R – heat-removal coefficient
- $(\tau\alpha)$ – transmittance-absorptance product
- I_T – global radiation, W/m^2
- I_R – reflection radiation from the mirror, W/m^2
- ω – time interval corresponding to hour angle, sec.
- $f_A = A_R/A_C$ – area ratio
- A_R – area proportion of the collector receiving reflection radiation from the mirror, m^2

V primeru, ko sta površini sprejemnika in zrcala enaki in je kot med ploskvama 120° , potem je $f_A = 1$, če je ploskev sprejemnika vedno navpična glede na sončne žarke (premični tip). Pri nepremičnem tipu je f_A odvisen od kota sončnih žarkov (θ), kakor tudi od razmerja izmer sprejemnika $L = a/b$ (a,b dolžina/ višina sprejemnika).

In the case when the areas of the collector and mirror are the same and the angle between their planes is 120° , $f_A = 1$ if the collector's plane is always perpendicular to the solar beam (tracking type). For the non-tracking type, f_A depends on the incident angle of the solar beam (θ) as well as the dimension ratio of the collector, $L = a/b$ (a and b are the length and the width of the collector, respectively).

Ugotovljeno je, da neposredno in razpršeno sevanje površine sprejemnika ni odvisno od f_A . Največji problem je določitev razmerja med f_A in odbojnim sevanjem I_R in potem določitev največje absorbirane energije sprejemnika [2].

It is recommended that the direct and diffusion radiation which is incident on the collector's surface does not depend on f_A . So the important problem is how to determine the relation between f_A and the reflection radiation (I_R), and then to determine the maximum absorbed energy of the collector [2].

$$f_A = \begin{cases} 1 - \frac{\sqrt{3}}{2L} \operatorname{tg} \theta & \text{when } |\theta| \leq \arctan L / \sqrt{3} \\ \frac{L}{2\sqrt{3}} \operatorname{ctg} \theta & \text{when } |\theta| > \arctan L / \sqrt{3} \end{cases} \quad (2)$$

če je $|\theta| \leq \arctan L / \sqrt{3}$

when $|\theta| \leq \arctan L / \sqrt{3}$

če je $|\theta| > \arctan L / \sqrt{3}$

when $|\theta| > \arctan L / \sqrt{3}$

S kombinacijo enačb (1) in (2) ter upoštevanjem, daje $I_R = \mu I_b \cos \theta / 2$, kjer μ pomeni zrcalno odbojnost in I_b neposredno sevanje, dobimo:

Combining eqs. (1) and (2), and with the knowledge that $I_R = \mu I_b \cos \theta / 2$, where μ is the mirror's reflectance and I_b is the direct radiation, we have:

$$dQ_u = \left[A_c F_r (\tau\alpha) I_T + \mu A_c F_r (\tau\alpha) f_A I_b \frac{\cos \theta}{2} \right] d\omega \quad (3)$$

Pri izračunu ločimo sprejeto in odbito sevanje dQ_C in dQ_R :

For convenience, the collector's radiation and the reflection radiation can be separated as dQ_C and dQ_R , respectively:

$$dQ_R = \mu A_C F_R (\tau\alpha) f_A I_b \frac{\cos \theta}{2} d\omega \tag{4}$$

Ker je razmerje med sončnim urnim kotom ω in kotom sončnih žarkov θ sorazmerno s sončnim gibanjem, je simetrično s ploskvijo sprejemnika (pred sončnim poldnevom in po njem):

$$\theta = \frac{\pi}{2} \frac{\omega}{\Delta\omega} \quad \text{ali/or} \quad d\omega = 2 \frac{\Delta\omega}{\pi} d\theta \tag{5}$$

Because the relation between the hour angle (ω) and the incident angle (θ) is linear and the sun's movement is symmetrical to the collector's plane (before and after solar noon):

Če vstavimo $B = L/\sqrt{3}$ in integriramo (4), dobimo: Put $B = L/\sqrt{3}$ and taking the integral for (4) we have:

$$Q_R = \frac{\Delta\omega}{\pi} \mu A_C F_R (\tau\alpha) I_b \left(-B \ln \left| \frac{1}{B} (\sqrt{1+B^2} - 1) \right| + \frac{1}{B} (\sqrt{1+B^2} - 1) \right) \tag{6}$$

podobno:

similary:

$$Q_C = 4 \frac{\Delta\omega}{\pi} A_C F_R (\tau\alpha) I_b + 2\Delta\omega A_C F_R (\tau\alpha) I_d \tag{7}$$

Prvi del enačbe pomeni neposredno sevanje Q_{Cb} , drugi del pa razpršeno sevanje Q_{Cd} .

The first term of eq. (7) is the direct radiation energy (Q_{Cb}) and the second term is the diffusion energy (Q_{Cd}).

Ugotovljeno je bilo, da je Q_R zelo odvisen od parametra B , oziroma od razmerja L . Iz tega izhaja, da izbira razmerja dimenzij L vpliva na količino absorbirane energije in s tem na učinkovitost sprejemnika.

It is recommended that Q_R depends very much on the parameter B , i.e on the ratio L . So the selection of the dimension ratio L would affect the absorbed energy and the efficiency of the collector.

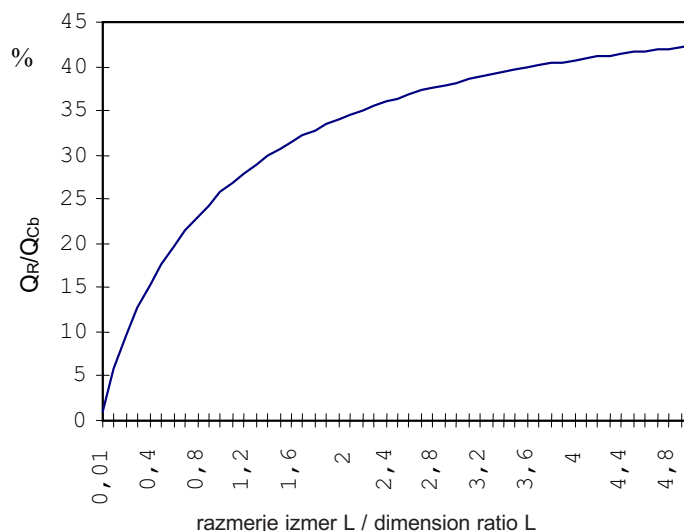
Določitev razmerja $Q_R/Q_{Cb} = f_B$, ki je funkcija B v %

Symbolizing the ratio Q_R/Q_{Cb} to be f_B as a function of B , %

$$f_B = Q_R / Q_{Cb} = \frac{\mu}{4} \left(-B \ln \left| \frac{1}{B} (\sqrt{1+B^2} - 1) \right| + \frac{1}{B} (\sqrt{1+B^2} - 1) \right) \tag{8}$$

in predstavitev razmerja med f_B in L na sliki 1. Iz tega lahko vidimo sprejemljivo razmerje, da pri $L = 1,7$ do 3 dobimo 32% do 38% več neposrednega sevanja (z uporabo močno odbojnega stekla zrcala, $\mu \approx 1$).

and expressing the relation between f_B and L in Fig. 1, it can be seen that a reasonable ratio of $L = 1.7$ to 3 will result in 32% to 38% more direct radiation (when a glass mirror of high reflectance is used, i.e $\mu \approx 1$).



Sl. 1. Razmerje med f_B in L
 Fig. 1. Relation between f_B and L

2 OPTIMIRANJE IZMER
SPREJEMNIK – ZRCALO

Za določitev optimalnega razmerja L za kombinacijo sprejemnik – zrcalo moramo upoštevati stroške porabe energije in izdelave sprejemnika.

Z uporabo odbojnega zrcala so povprečni mesečni stroški za električno energijo E družine nižji. Zmanjšanje stroškov ΔE je posledica razmerja izmer L , kar je razvidno iz funkcije Q_R .

$$\Delta E = 30 \cdot 10^{-6} p Q_R \quad \begin{matrix} \text{USD/mesec} \\ \text{USD/month} \end{matrix} \quad (9)$$

kjer so:

- Q_R – absorbirana odbojna energija v J
- p – cena energije na enoto, VND/MJ
- 30 – povprečno št. dni v mesecu
- Tako znašajo mesečni stroški:

$$E_a = E - \Delta E \quad \begin{matrix} \text{USD/mesec} \\ \text{USD/month} \end{matrix} \quad (10)$$

Stroški sistema C kombinacije sprejemnik – zrcalo se linearno zvečuje z L , in so določeni tudi z dobo trajanja [3]. Predpostavljamo, da je doba trajanja sistema 5 in 10 let:

$$C = P \frac{i(1+i)^n}{(1+i)^n - 1} L, \quad \begin{matrix} \text{USD/mesec} \\ \text{USD/month} \end{matrix} \quad (11)$$

kjer so:

- P – stroški sprejemnik – zrcalo v USD/m²
- i – mesečna obrestna mera v %
- n – doba trajanja v mesecih, 60 ali 120 mesecev

Slika 2 prikazuje odvisnost E_a in C od razmerja dimenzij L pa tudi celotne stroške $E_t = (E_a + C)$, kjer so E_{t5}, E_{t10} in C_5, C_{10} vrednosti E_t in C za 5 in 10 let dobe trajanja.

2 OPTIMIZATION OF THE COLLECTOR-MIRROR
DIMENSIONS

To fully evaluate an optimal ratio of L for the collector-reflector combination, the cost of energy consumption and collector manufacturing should be included.

Using a reflection mirror can make the monthly average expenditure on electrical consumption (E) for a family lower and the dependence of the expenditure reduction (ΔE) on the dimension ratio (L) is a function of Q_R .

$$\Delta E = 30 \cdot 10^{-6} p Q_R \quad \begin{matrix} \text{USD/mesec} \\ \text{USD/month} \end{matrix} \quad (9)$$

where :

- Q_R – useful energy absorbed from the reflection radiation, J
- p – power unit price, VND/ MJ
- 30 – average days per month
- So, actual monthly expenditure will be :

$$E_a = E - \Delta E \quad \begin{matrix} \text{USD/mesec} \\ \text{USD/month} \end{matrix} \quad (10)$$

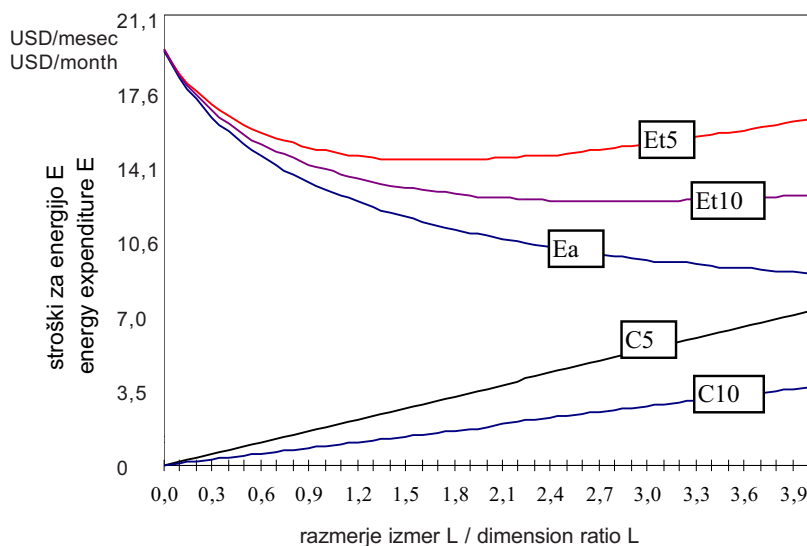
The installation cost (C) of a collector-reflector combination is linearly proportional to L and determined by different life-times of the combination [3]. Assuming the life-time of the equipment to be 5 and 10 years:

$$C = P \frac{i(1+i)^n}{(1+i)^n - 1} L, \quad \begin{matrix} \text{USD/mesec} \\ \text{USD/month} \end{matrix} \quad (11)$$

where:

- P – collector-reflector cost, USD/m²
- i – monthly interest rate, %
- n – months of life-time, 60 or 120 months

Figure 2 shows the dependence of E_a and C on the dimension ratio (L), as well as the total expenditure $E_t = (E_a + C)$ on L , in which E_{t5}, E_{t10} and C_5, C_{10} are the values of E_t and C for 5 and 10 years of life-time, respectively.



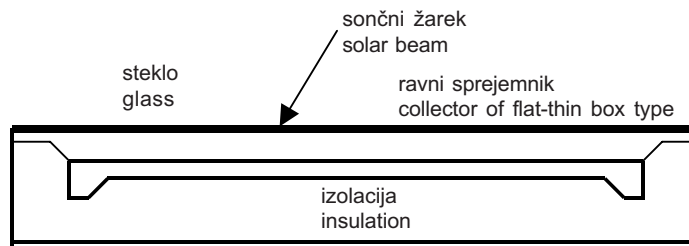
Sl. 2. Stroški energije E_t v odvisnosti od razmerja izmer
Fig. 2. Energy Expenditure (E) vs Dimension Ratio L

Jasno je, da dosežejo povprečni mesečni stroški za energijo najmanjšo vrednost takrat, kadar je $L = 1,7$ do 3 (kar ustreza dobi trajanja sprejemnika 5 ali 10 let). To vrednost razmerja izmer svetujejo za uporabo načrtovanja in izdelave sončnih sprejemnikov v Vietnamu (in morda tudi v drugih manj razvitih državah).

3 PRESKUS SPREJEMNIKOV RAZLIČNIH RAZMERIJ IZMER

Proučevali so kombinacijo sprejemnik – zrcalo. Sestavljeno je iz treh ploščatih sprejemnikov dimenzij $1,0 \times 1,3$ m in treh zrcal enakih izmer (razmerja izmer $L_1 = 0,77$, $L_2 = 1,54$, $L_3 = 2,31$). Ta sestav sprejemnika je prikazan na sliki 3.

Raziskovalno delo temelji na učinkovitosti in energijski enačbi sprejemnika [1]:



Sl. 3. Struktura sprejemnika

Fig.3. The collector structure

$$\eta_i = \frac{Q_u}{A_c I_T} = F_R (\tau \alpha) - F_R U_L \frac{T_i - T_a}{I_T} \quad (12)$$

in

and

$$Q_U = m C_p (T_o - T_i) \quad (13),$$

kjer so T_i , T_o , T_a : vstopna, izstopna temperatura delovnega fluida in temperatura okolja, C_p specifična toplota vode v J/kgK.

Strukturni parametri sprejemnika so naslednji:

- izmere ploščatega sprejemnika: $L \times W \times D = 1220$ mm x 920 mm x 5 mm
- izmere posameznega sprejemnika: $L \times W \times D = 1300$ mm x 1000 mm x 100 mm
- količina vode v posameznem sprejemniku: 5,98kg
- debelina stekla: 3 mm
- prostor med steklom in ploščato površino: 35 mm
- material absorberja: galvanizirana plošča: 0,8 mm (brez selektivnega nanosa).

3.1 Določitev značilnih parametrov sprejemnika

Za preskus so potrebni naslednji podatki:

- celotno sončno sevanje I_T v W/m^2
- celotna sončna energija Q_T v J/m^2
- vstopna in izstopna temperatura vode T_{fi} in T_{fo} v K

It is clear that the monthly average expenditure for energy consumption is a minimum value in the interval of $L = 1.7$ to 3 (corresponding to a life-time of the collector of 5 or 10 years). So this value of the dimension ratio is suggested for use when designing and manufacturing a solar collector in Vietnam (and maybe in some other less-developed countries).

3 TESTING A COLLECTOR OF DIFFERENT DIMENSION RATIOS

A collector-reflector combination has been investigated. It has 3 flat-plate collectors of 1.0×1.3 m with 3 mirrors of the same dimension (dimension ratios $L_1 = 0.77$, $L_2 = 1.54$, $L_3 = 2.31$). The collector structure is shown in Fig.3.

The experimental work is based on the efficiency expression and energy equation of the collector [1]:

where T_i , T_o , T_a are the outlet and inlet temperature of the working fluid and the ambient temperature, respectively. C_p is the specific heat capacity of water, J/kg.K.

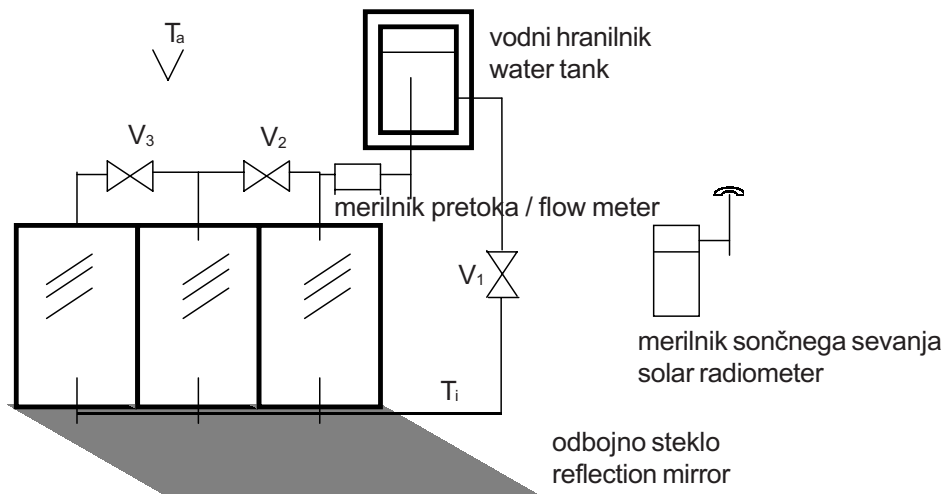
The structural parameters of the collector are as follows:

- dimensions of flat-thin box: $L \times W \times D = 1220$ mm x 920 mm x 5 mm
- packaged dimensions of collector unit: $L \times W \times D = 1300$ mm x 1000 mm x 100 mm
- water weight of collector unit: 5.98 kg
- glass thickness: 3 mm
- space between the glass and the flat-thin box surface: 35 mm
- flat-thin box material: galvanized sheet 0.8 mm (no selective coating).

3.1 Determining characteristic parameters of the collector :

Experiment data required :

- global solar radiation (I_T), W/m^2
- global solar energy (Q_T), J/m^2
- inlet and outlet water temperature (T_{fi}) and (T_{fo}), K



Sl. 4. Eksperimentalni načrt
Fig. 4. Experimental scheme

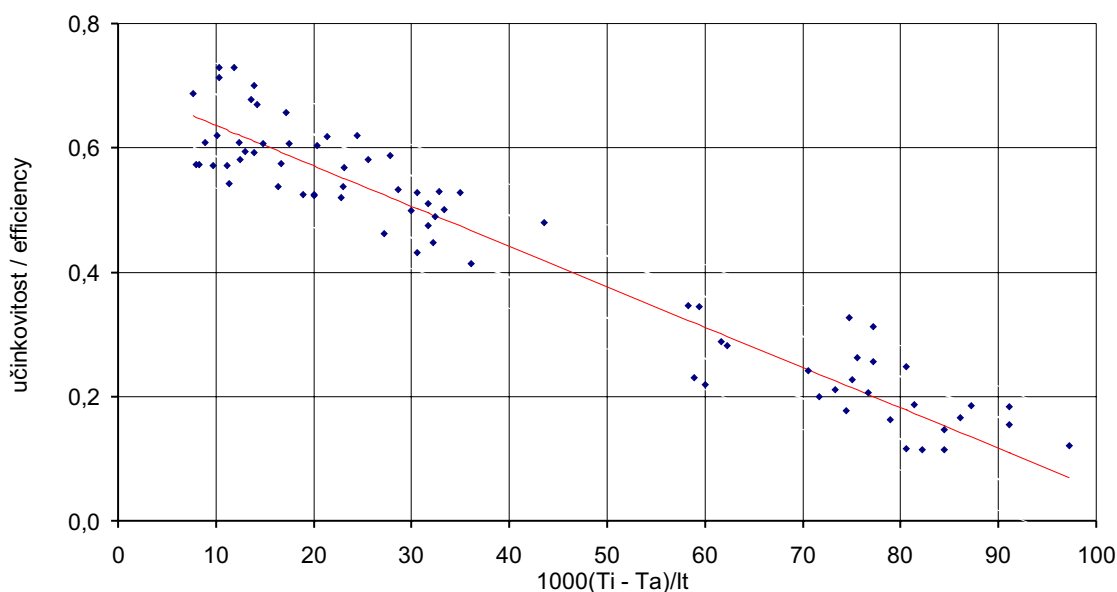
- temperatura okolja T_a v K
- masni tok vode m v kg/s.

Z uporabo enačb (12) in (13) pridemo do razmerja med učinkovitostjo sprejemnika in $(T_i - T_a)/I_T$, karakteristični parametri sprejemnika so znani (sl. 5):

- ambient temperature (T_a), K
- water flow rate (m), kg/s

Using eqs. (12) and (13) to establish the relation between the collector efficiency and $(T_i - T_a)/I_T$, the characteristic parameters of the collector can be found (Fig. 5):

$$F_R(\tau\alpha) = 0,708 \quad \text{in / and} \quad F_R U_L = 6,49 \text{ W/m}^2\text{K}$$



Sl. 5. Učinkovitost sprejemnika v odvisnosti od $(T_i - T_a)/I_T$
Fig. 5. Collector efficiency vs $(T_i - T_a)/I_T$

3.2 Določanje sprejemnika glede na različna razmerja izmer

Preskus je bil opravljen s tremi različnimi razmerji izmer: $L_1 = 0,77$; $L_2 = 1,54$; $L_3 = 2,31$.

Potrebni eksperimentalni podatki:

- temperatura okolice T_a v K,
- povprečna temperatura vode v rezervoarju T_f in

3.2 Determining the dependance of the collector on the collector dimension ratio.

Experiments were carried out using 3 different dimension ratios : $L_1 = 0,77$; $L_2 = 1,54$ and $L_3 = 2,31$.

Experimental data equired:

- ambient temperature (T_a), K,
- average water temperature in the tank (T_f) and

vstopna temperatura vode T_i v K,
 - celotno sevanje I_T v W/m^2 in celotna globalna energija G_T v J/m^2 .

inlet water temperature (T_i), K,
 - Global Radiation (I_T), W/m^2 and global radiation energy (G_T), J/m^2 .

Energijo, ki je na voljo, določimo iz obrazca:

In this experiment, the useful energy can be calculated as:

$$Q_u = MC_p(\Delta T_f) \tag{14}$$

kjer je:

where:

M - masa vode v sprejemniku, hranilniku in cevovodu v kg

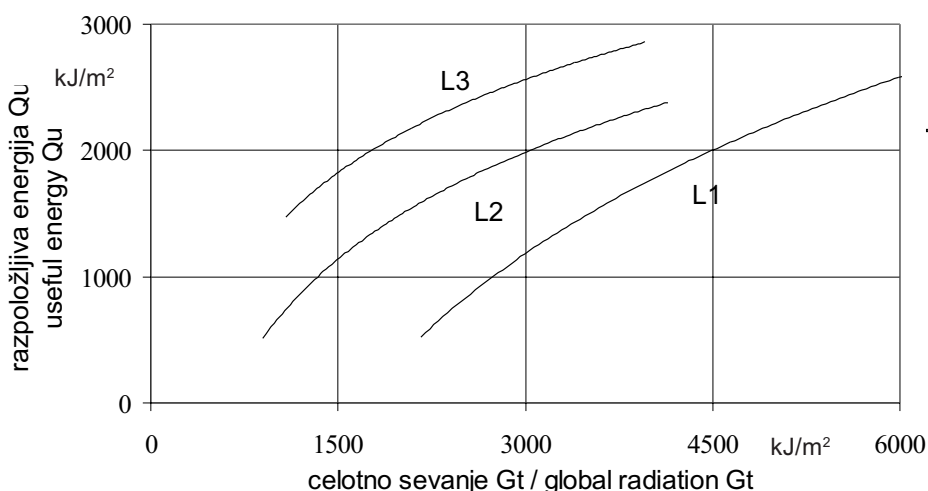
M - mass of water in the system of collector, water tank and connection pipe, kg

ΔT_f - sprememba povprečne temperature v rezervoarju v K.

ΔT_f - average water temperature difference in the tank, K

Odvisnost razpoložljive energije Q_u od razmerja dimenzij L in globalnega sevanja G_T je vidna na sliki 6.

The dependance of the useful energy (Q_u) on dimension ratio (L) and global radiation (G_T) can be seen in Fig.6.



Sl. 6. Energija, ki je na voljo, v odvisnosti od razmerja izmer
 Fig. 6. Useful energy of the collector with different dimension ratio

4 SKLEP

4 CONCLUSIONS

Ravni sprejemnik sončne energije z galvanizirano ploščo ima sprejemljive značilnosti parametrov, ki so podobni cevnim, vendar so preprostejši za izdelavo in nimajo selektivnega nanosa. Z uporabo nepremičnega zrcala lahko dosežemo višjo temperaturo delovnega fluida, v dneh zmernega sevanja (pod $800 W/m^2$) doseže temperatura v hranilniku tudi $97\text{ }^\circ\text{C}$. Tako visoke temperature delovne tekočine so potrebne za absorpcijski hladilni krog. Z uporabo optimalnega razmerja izmer sprejemnik – zrcalo dobimo od 33 do 38% več neposrednega sevanja in večjo učinkovitost (glej sliko 1 in podatke spodaj).

The solar collector of the flat-thin box type made of galvanized sheet has acceptable characteristic parameters, which are similar to that of the tube-sheet type of collector but it is simpler to fabricate and has no selective coating. Using a fixed reflection mirror can make the temperature of the working fluid higher: on days of moderate radiation (below $800 W/m^2$), the water temperature in the tank could reach 97°C . Such a high temperature of the working fluid is necessary for the absorption-refrigeration cycle. By taking an optimal dimension ratio for the collector-reflector design it is possible to get 33% to 38% more direct radiation as well as higher efficiency (see Fig.1 and the data below).

L	0,77	1,54	2,31
$F_R(\tau\alpha)$	0,737	0,7545	0,7679
$F_R U_L, W/m^2K$	6,9332	6,7907	6,543
$\eta_{av}, \%$	19,3	36,5	57

Ta model kombinacije sprejemnik – zrcalo je uporaben v nekaterih tropskih državah za razvoj vodnega sončnega ogrevanja (VSO - SWH) ali sončnega absorpcijskega hlajenja (SOH - SAR).

So this design of the collector-reflector combination may be used in some tropical countries to develop a solar water heater (SWH) or a solar absorption refrigerator (SAR).

5 LITERATURA

5 REFERENCES

- [1] Duffie, J.A., W.A. Beckman (1991) Solar engineering of thermal processes (3rd edition). *John Willey & Sons, Inc.*
- [2] Quan, N. (1999) A new design of solar absorption refrigerator with collector-reflector combination of fixed type. *Proceedings of 20th International Congress of Refrigeration*, Sydney, Australia.
- [3] Stoecker, W.F. (1989) Design of thermal systems, (3rd edition). *McGraw-Hill Book Co.*

Naslov avtorjev: Dr. Ha Dang Trung
Nguyen Quan
Tehnična univerza Hanoi
1. Dai Co Viet Road
Hanoi, Vietnam

Author's Address: Dr. Ha Dang Trung
Nguyen Quan
Hanoi University of Technology
1. Dai Co Viet Road
Hanoi, Vietnam

Prejeto: 15.8.2000
Received:

Sprejeto: 10.11.2000
Accepted: