

ESTIMATING THE EFFECT OF SELECTIVE ABSORBER ON CSP-COLLECTOR PERFORMANCE

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ABSTRACT

Spectrally-selective absorbers are used in CSP solar collectors to enhance the net solar input, to the collector, and reduce energy loss, by radiation, from the absorber. This double-fold effect should be more fruitful in concentrating collectors where the absorbers are operating at high temperatures ; and, hence, the energy loss is dominantly due to radiation specially in evacuated absorbers.

First, the rudiments of the subject are briefly overviewed. The characteristics of some of the currently-available selective surfaces are cited. These examples are meant to indicate the achievable levels of selectivity. This is a necessary steppingstone to the evaluation of selectivity effect on CSP-collector performance.

An analytical investigation of the gain in collector efficiency, achieved by using a selective absorber, is herein presented. Formulae are derived which allow for the estimation of efficiency rise. The governing factors are identified and expressed in terms of relevant variables.

The percentage gain in collector efficiency was found to be dependent on three dimensionless parameters. Two of them are related to the radiation properties of the absorber surface ; while the third is related to the thermal efficiency of non-selective collector which is a component, or ingredient, of the collector efficiency. The trend of variation, with each of these parameters, is determined ; and graphically illustrated. Numerical values of the percentage efficiency improvement are graphically presented for different values of the three independent parameters.

1. INTRODUCTION

Low-temperature applications of solar energy have been

in wide use for an extended duration ; long before the modern onset of high-temperature utilizations realized by “Concentrated-Solar-Power” CSP technologies. Based on the long practice, with numerous designs with and without selective absorbers, extensive knowledge has been accumulated. The benefit of introducing selective absorbers, in flat-plate collectors FPC, has been practically proven and definitely evaluated. The general trends of the standardized efficiency curves, of selective and non-selective FPC, are illustrated in Fig. 1. This reveals that spectral selectivity improves the efficiency and, also, extends the operating range beyond the stagnation temperature of non-selective collector. Numerical quantifications are available for commercial products.

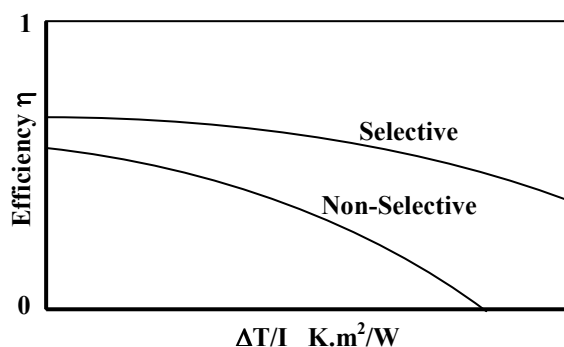


Fig. 1 Efficiency curves for selective and non-selective FPC.

On the other hand, detailed information about the role of spectrally-selective absorbers in improving the CSP-systems performance is rather limited. This may be attributed to two facts. First, is the relatively short period of practicing with CSP systems. Second, is the absence of a large diverse market including a wide variety of commercial products. However, the adoption of spectrally-selective surfaces in CSP collectors should logically have more contribution, to performance improvement, than in FPC ; due to the following reasons.

The absorbers of CSP collectors are intended to be operating at high temperatures where radiation is the predominant mode of energy loss. Moreover, CSP absorbers are frequently evacuated to reduce, or eliminate, convective loss. Therefore, it is of utmost importance to have a quantitative idea about the positive gain, in collector efficiency, achieved by the introduction of spectrally-selective absorber surfaces. Of course, this can always be precisely evaluated through actual operation. However, an analytical tool would be helpful in making beforehand estimations. This work presents an approximate analysis through which the gain in efficiency will be worked out.

2. THE IDEAL SELECTIVE SURFACE

The implementation of spectral selectivity in a solar collector makes use of the wide spectral difference between the incoming solar radiation and the thermal radiation emitted back from the absorber. A comparison between the received solar radiation and the thermal radiation lost from the absorber surface is illustrated in Fig. 2 for three source temperatures. The ordinate of this figure is normalized relative to the peak intensity.

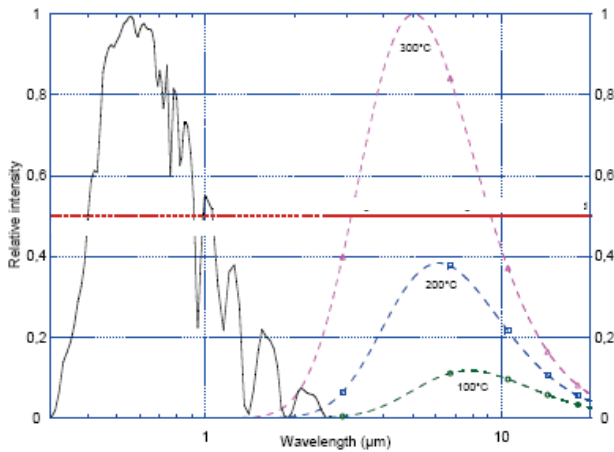


Fig. 2 Comparison between solar and thermal radiation on a wavelength scale [1].

The figure shows that the received solar radiation and the thermal radiation emitted back from the absorber surface have two distinct zones along the electromagnetic spectrum. It can be stated that, as a rule of thumb, about 98.5% of the solar-energy input is distributed over wavelengths less than about 2.5 μ . For collector absorbers operating, for example, in the temperature range of 100 - 300°C the peak emission would be in the approximate wavelength-range of 8 - 5 μ . Less than 2 % of the total energy radiated at these temperatures falls at wavelengths below 2 - 3 μ . The spectral overlap between the two zones is very limited. Accordingly, the idea, of implementing spectral selectivity, is to create the absorber surface, or treat it, in such a way as to enhance the absorption of short-wave solar radiation and, at the same

time, suppress the emission of long-wave thermal radiation.

With the objective of selectivity made clear, it is possible to identify what may be defined as the ideal, or perfect, selective surface. The spectral reflectance, or reflectivity, of such an imaginary surface is shown in Fig. 3. It should have a zero reflectance all over the domain $0 < \lambda < \lambda_c$; and a reflectance of unity for all wavelengths $\lambda > \lambda_c$ where λ_c is a “critical” or “cutoff” wavelength which will be arbitrarily selected in or around the range 2-3 μ depending on the absorber operating temperature. Accordingly, and since the absorber-surface is opaque, the spectral absorptance, or absorptivity, along the left-hand part of Fig. 3 will be

$$\alpha_{\text{sol}} = 1 \quad \text{for } 0 < \lambda < \lambda_c \quad (1)$$

which means that the surface will be a perfect absorber of the short-wave solar radiation. On the other hand, the spectral absorptivity throughout the right-hand part of Fig. 3 will be

$$\alpha_{\text{therm}} = 0 \quad \text{for } \lambda > \lambda_c \quad (2)$$

where the subscripts (sol) and (therm) stand for solar and thermal radiation respectively.

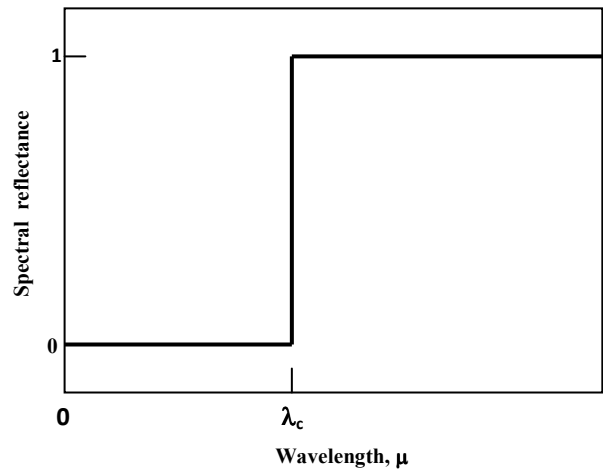


Fig. 3 Spectral reflectance of the ideal selective surface [2].

Based on Kirchhoff’s identity, the spectral emittance, or emissivity, is equal to the spectral absorptance. Thus,

$$\epsilon_{\text{therm}} = 0 \quad \text{for } \lambda > \lambda_c \quad (3)$$

This means that the absorber surface will not emit any long-wave thermal radiation.

3. QUANTIFYING THE EXTENT OF SELECTIVITY

In reality, the idealized performance of the perfect selective surface, shown in Fig. 3, as a perfect, or ideal,

“reflection-absorption high-pass filter” cannot be practically realized. The extreme-limiting reflectivity values of zero and unity will never be completely achieved with real surfaces. The best we can hope for is to have spectral reflectivities as low as possible in the range $0 < \lambda < \lambda_c$ and as high as possible in the range $\lambda > \lambda_c$. Moreover, the switching from low to high reflectivities will never take place as abruptly as shown in Fig. 3 ; the change will certainly extend over a finite wavelength band.

The spectral reflectances of a number of real selective surfaces are shown in Figs. 4 to 6 ; as typical examples of the achievable levels of selectivity. Moreover, numerical values of the properties of some high-performance surfaces, intended for high-temperature applications, are listed in Table 1.

The extent of selectivity will be expressed by the “Selectivity” or “Degree of Selectivity” S [6]. This is defined as

$$S = \alpha_{\text{sol}} / \epsilon_{\text{therm}} \quad (4)$$

where α_{sol} is the average absorptivity over the solar spectrum (left of the cutoff wavelength) and ϵ_{therm} is the average emissivity over the thermal-radiation spectrum (right of the cutoff wavelength).

Another, alternative, index is also used to indicate the achieved extent of selectivity. This is the “Merit Function” F [7] ; defined by

$$F = \alpha_{\text{sol}} (1 - \epsilon_{\text{therm}}) \quad (5)$$

Either of the two indices will serve the purpose. But, the merit function has a further advantage. It has a theoretical ceiling of unity ; for the ideal selective surface. So, its value will always be confined to $F < 1$. A value on the zero-to-one scale can be easily perceived and evaluated.

Table 1 shows that degrees of selectivity well above 25 have been realized. Merit functions as high as 0.9 have been attained.

4. ANALYSIS

Ignoring the contribution of diffuse radiation, which is true for most types of concentrating collectors specially imaging ones, the efficiency of a collector with a non-selective absorber will be given by

$$\eta = \eta_{\text{opt}} - \frac{U_L (t_s - t_a)}{CI_D} \quad (6)$$

where

η_{opt} is the collector optical efficiency
 U_L is the overall heat-loss coefficient from absorber surface, $W/m^2 \cdot ^\circ C$

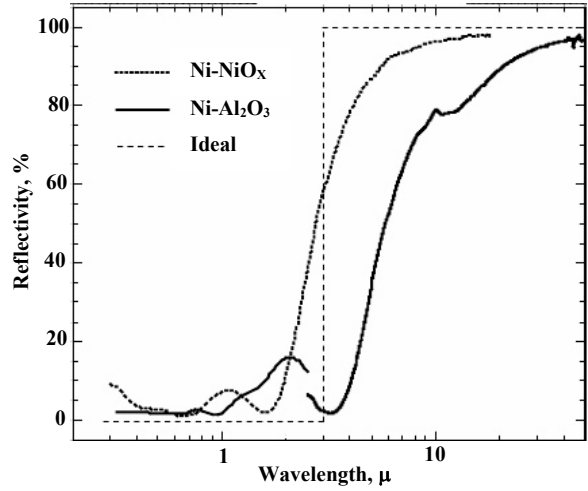


Fig. 4 Spectral reflectivity of two selective surfaces using Ni-based films [3].

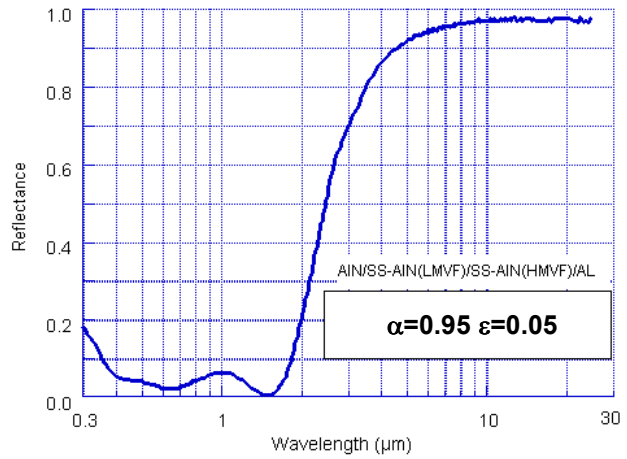


Fig. 5 Spectral reflectivity of a surface with double SS/AIN cermet layers [4].

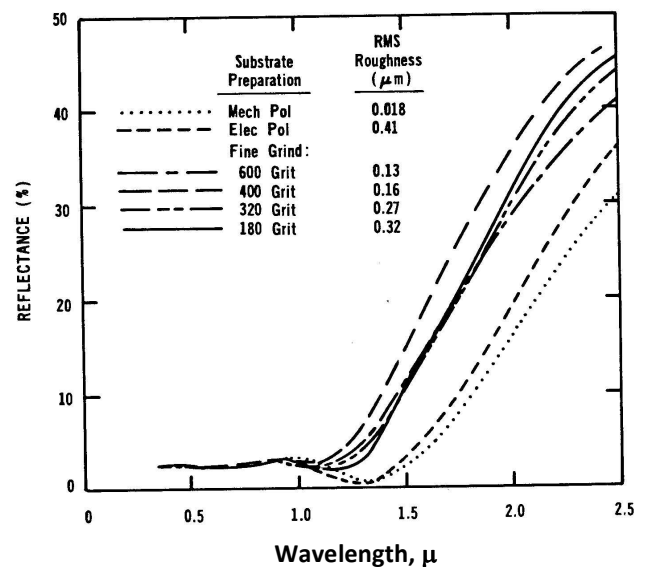


Fig. 6. Reflectance of black-chrome coating on substrates of different roughness [5].

TABLE 1 : CHARACTERISTICS OF SOME SELECTIVE SURFACES

Surface		α_{sol}	ϵ_{therm}	Source
Black nickel	NiS-ZnS	0.96-0.98	0.03-0.1	[6]
Black chrome	Cr-Cr ₂ O ₃	0.97	0.09	[6]
Black copper	BiCu-Cu ₂ O : Cu	0.97-0.98	0.02	[6]
Mo MgF ₂ TiO ₂	5 layers Planar	0.88	0.03	[7]
Mo MgF ₂ TiO ₂	5 layers V-grooved	0.92	0.05	[7]
Mo MgF ₂ TiO ₂	11 layers Planar	0.94	0.06	[7]
Mo MgF ₂ TiO ₂	11 layers V-grooved	0.96	0.08	[7]
Multilayer Al ₂ O ₃ -based cermet with AR coating		0.96	0.10	[8]
Black chrome		0.916	0.081 at 25°C 0.146 at 200°C 0.220 at 400°C	[8]
Mo-AlN	2 cermets	0.94	0.11	[9]
W-AlN	2 cermets	0.92	0.08	[9]
Black nickel on bright nickel		0.96	0.07	[10]
Black chrome on bright nickel		0.95	0.09	[10]
Co-Al ₂ O ₃		0.94	0.04	[11]
W-Al ₂ O ₃		0.97-0.98	0.07-0.1	[11]

t_s is the average temperature of absorber surface, °C
 t_a is the ambient temperature, °C
 C is the geometrical concentration ratio
 I_D is the direct-radiation flux on the aperture plane, W/m²

$$\eta_{opt} = \rho \cdot \gamma \cdot \tau \cdot \alpha \quad (7)$$

where

ρ is the reflectivity of mirror
 γ is the intercept factor of reflected radiation by the absorber
 τ is the transmissivity of glass shield
 α is the absorptivity of non-selective absorber surface

$$C = A_{ap} / A_{abs} \quad (8)$$

where

A_{ap} is the aperture area, m²
 A_{abs} is the absorber-surface area, m²

A fair assumption, which has been used before in the analysis of concentrating collectors will be adopted here. The thermal losses from the absorber surface will be assumed to be solely due to radiant heat transfer [12]. This is practically true because radiation is the dominant mode at elevated temperatures ; specially in collectors with evacuated absorbers. Thus, Eqn. (6) can be put in the form

$$\eta = \rho\gamma\tau\alpha - \frac{\epsilon\sigma(T_s^4 - T_a^4)}{CI_D} \quad (9)$$

where

ϵ is the non-selective absorber-surface emissivity
 σ is the Stefan-Boltzmann constant = 5.6697 x 10⁻⁸ W/m².K⁴

T_s and T_a are the average absorber-surface and ambient absolute temperatures, K

Based on Kirchoff's identity for the non-selective absorber surface

$$\alpha_\lambda = \epsilon_\lambda$$

and considering the absorber surface to be a gray surface, then the total properties are related by

$$\alpha = \epsilon$$

and Eqn. (9) can be put in the form

$$\eta = \frac{\epsilon\sigma(T_s^4 - T_a^4)}{CI_D} \left[\frac{(\rho\gamma\tau)CI_D}{\sigma(T_s^4 - T_a^4)} - 1 \right] \quad (10)$$

For a collector with a selective absorber, Eqn. (9) takes the form

$$\eta_s = (\rho\gamma\tau)\alpha_{sol} - \frac{\epsilon_{therm}\sigma(T_s^4 - T_a^4)}{CI_D} \quad (11)$$

where the subscript s stands for "selective absorber". Consequently,

$$\eta_s = \frac{\varepsilon_{therm} \sigma (T_s^4 - T_a^4)}{CI_D} \left[\frac{(\rho\gamma\tau) CI_D (\alpha_{sol} / \varepsilon_{therm})}{\sigma (T_s^4 - T_a^4)} - 1 \right] \quad (12)$$

The percentage gain in collector efficiency, achieved by using a spectrally-selective absorber surface, can be evaluated from

$$\% \text{age gain} = G = \frac{\eta_s - \eta}{\eta} \times 100 = \left(\frac{\eta_s}{\eta} - 1 \right) \times 100 \quad (13)$$

Using Eqns. (10) and (12) in Eqn. (13), results in

$$G = \left\{ \frac{\varepsilon_{therm}}{\varepsilon} \left[\frac{N(\alpha_{sol} / \varepsilon_{therm}) - 1}{N - 1} \right] - 1 \right\} \times 100$$

$$= \left\{ R \left[\frac{N.S - 1}{N - 1} \right] - 1 \right\} \times 100 \quad (14)$$

where the dimensionless group N is given by

$$N = \frac{(\rho\gamma\tau) CI_D}{\sigma (T_s^4 - T_a^4)} \quad (15)$$

and R is the ratio $\varepsilon_{therm} / \varepsilon$.

Equation (14) reveals that the percentage gain in collector efficiency is a function of three dimensionless parameters. These are the dimensionless group N, the degree of selectivity S and the ratio R. The lumped parameter N is important ; and is worth further discussion.

The physical meaning of the number N can be found by multiplying the numerator and denominator, in Eqn. (15), by α and ε respectively (keeping in mind that they are equal) ; and writing the concentration ratio C in the form A_{ap}/A_{abs} . This will divulge that for non-selective absorbers

$$N = (\text{Power absorbed by absorber}) / (\text{Power lost from absorber}) \quad (16)$$

Based on this definition, the theoretical minimum value N can assume is unity ; which represents the practically-insignificant case of zero collector output. This can also be further explained by combining Eqns. (9) and (10) to yield

$$\eta = (\rho\gamma\tau) \alpha \left(1 - \frac{1}{N} \right) \quad (17)$$

This asserts that the non-selective collector efficiency η will tend to zero when N drops to unity. Accordingly, any value of $N < 1$ would be a violation of the first law of thermodynamics ; since it means that the losses from the absorber are larger than the input to it.

The theoretical maximum limit of N is associated with the theoretical case when the collector efficiency η reaches to its maximum limit which is the optical efficiency η_{opt} defined in Eqn. (7). It can be seen, from Eqn. (17), that the theoretical maximum value is $N = \infty$. However, this

infinitely-high limit of N has no practical importance since it implies a thermal efficiency of 100%.

A practical range of N can be found by assigning a practical value to η . The efficiency η is equal to ($\eta_{opt} \eta_{therm}$) where η_{therm} is the thermal efficiency. Then, the value of N can be found, from Eqn. (17), to be

$$N = \frac{1}{1 - \eta_{therm}} \quad (18)$$

It should be noted that if the power loss is replaced, in the denominator of the right-hand side of Eqn. (16), by the difference between the absorbed power and the collector output, Eqn. (16) will be transformed to Eqn. (18). The relation between the parameter N and η_{therm} is displayed in Fig. 7 ; the efficiency axis is extended, from both ends, to impractical values for the sake of completing the picture. The parameter N tends to unity at $\eta_{therm} = 0$.

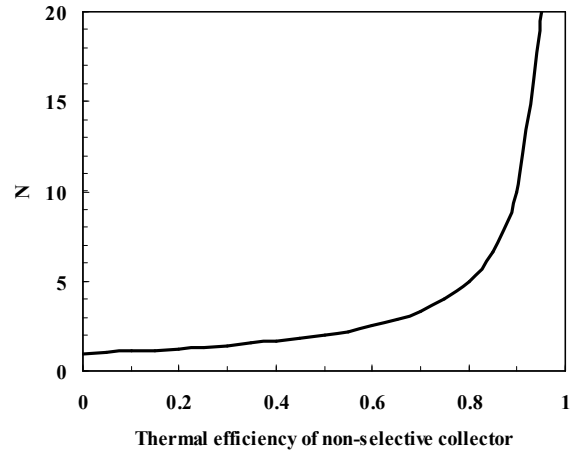


Fig. 7 Relation between N and η_{therm} .

Differentiating Eqn. (14) with respect to the three independent parameters, each at a time, results in

$$\frac{dG}{dN} \quad \text{is always negative}$$

$$\frac{dG}{dS} \quad \text{is always positive}$$

$$\frac{dG}{dR} \quad \text{is always positive}$$

which means that the percentage gain G will be monotonically increasing upon the decrease of N and/or the increase of S and/or R. Some general variation trends are sketched in Fig. 8. All curves, for all degrees of selectivity ($\alpha_{sol}/\varepsilon_{therm}$), tend to be asymptotic to the vertical $N = 1$; because any efficiency improvement starting from zero efficiency would represent an infinitely-large change.

The increase of efficiency gain at higher degrees of selectivity is logical and readily expected ; hence, it

requires no explanation. On the other hand, the increase of G with the ratio R may seem to be rather paradoxical since it insinuates a higher value of $\varepsilon_{\text{therm}}$ and, consequently, higher thermal loss. This can be explained based on the fact that with a constant degree of selectivity, $(\alpha_{\text{sol}}/\varepsilon_{\text{therm}}) > 1$, the increase of the ratio $(\varepsilon_{\text{therm}}/\varepsilon)$ will be outweighed by an increase in the ratio $(\alpha_{\text{sol}}/\alpha)$.

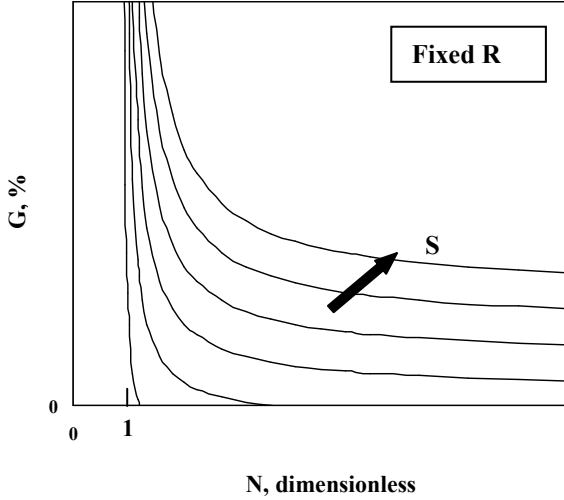


Fig.8 General trends of efficiency gain due to selectivity.

Typical values of percentage gain in efficiency are shown in Fig. 9 ; for different values of N , degree of selectivity and the ratio $(\varepsilon_{\text{therm}}/\varepsilon)$. The general trends, shown before in Fig. 8 are obviously maintained. But, Fig. 9 is confined to practical ranges which may be encountered in actual practice. The variations in curve profiles and the disappearance of some curves at low values of $(\varepsilon_{\text{therm}}/\varepsilon)$ need to be further explained.

The value of N at which a curve intersects the abscissa, i.e. $G = 0$, will be denoted by N_0 . Its value can be found, from Eqn. (14), to be

$$N_0 = \frac{1-R}{1-S.R} \quad (19)$$

This expression indicates that, since $R < 1$, there are three different possibilities :

- 1- Degree of selectivity $S < 1/R$
 N_0 has a positive practically-possible value
- 2- Degree of selectivity $S = 1/R$
 N_0 has an infinite value
- 3- Degree of selectivity $S > 1/R$
 N_0 has a negative value ; which cannot physically exist.

The efforts in development of selective surfaces result in the production of surfaces characterized by high degrees

of selectivity. Therefore, it may be important to go into details of the variation of the efficiency gain with the degree of selectivity. Equation (14) can be put in the form

$$G = B.S - D \quad (20)$$

where

$$B = 100.RN/(N-1) \quad (21)$$

$$D = 100.(1 + R/(N-1)) \quad (22)$$

If N and R are fixed, Eqn. (20) represents a straight-line relation. The variation trends implied by this equation are explained by the diagrammatic illustration in Fig. 10 ; where lines in the unacceptable negative domain of G are shown dotted. For a fixed value of R , the line slope B decreases upon the increase of N ; while the magnitude of the ordinate intersection $|D|$ decreases. All lines, for different values of N , pass through a common point at $S=1$; because at this value of S , the value of G , as given by Eqn. (14) or (20), would be $100(R-1)$; i.e. independent of N . Actual linear trends are shown in Fig. 11; based on typical calculated values of the parameters.

An important fact can be concluded from Fig. 10. A positive gain in the collector efficiency can be realized only if the degree of selectivity exceeds a certain limit. This threshold value of S , denoted by S_0 , is indicated, in Fig. 10, by the intersection of any of the lines with the abscissa. It can be determined, by equating G in Eqn. (14) to zero, as

$$S_0 = \frac{1}{R} \left[1 - \frac{(1-R)}{N} \right] \quad (23)$$

This equation can also be seen as a transposition of Eqn. (19). But, specifying the threshold limit in terms of the degree of selectivity S is more comprehensible.

The variation of the limit S_0 with N and R is displayed in Fig. 12. The common point, for all curves, is the point (1,1). As the parameter N increases, beyond a certain limit, the value of S_0 tends to be almost asymptotic. This explains the obvious crowd of high- N lines in Fig. 11.

5. CONCLUSION

The efficiency of a CSP collector can be appreciably improved by using a spectrally-selective absorber. Various types of selective surfaces are currently available ; with high levels of selectivity.

The enhancement of collector efficiency can be quantified by the formulae presented hereinbefore. The mathematical expressions are given in terms of the radiation properties of selective and non-selective surfaces ; in addition to other optical and concentrating characteristics as well as the operating conditions represented by the direct irradiance and the absorber and ambient temperatures.

In brief, the gain in collector efficiency is governed by

three dimensionless parameters ; S, R and N. The trends of variation of the efficiency gain with these parameters are determined and graphically illustrated. Higher efficiencies can be attained upon increasing S and/or R or decreasing N. Typical numerical values of the achievable efficiency gain are shown in Figs. 9 and 11.

The presence of the parameter N, among the governing parameters, reveals that the improvement in collector efficiency depends not only on the attained level of selectivity but also on other factors. These include some characteristics of the collector, unrelated to selectivity, as well as the operating conditions represented by I_D , T_s and T_a ; as shown in Eqn.(15). Speculating in Eqns. (14) and (15) and Figs. 7 to 11 will insinuate that only a small gain in efficiency can be realized in a collector with offhand-good efficiency. However, this should in no way be considered as an enticement to stop using selective surfaces in collectors with high performance. It should always be remembered that the gain G is a percentage of the non-selective efficiency. A small ratio of an already-high efficiency will represent, on an absolute scale, a gratifying reward.

A positive gain in the collector efficiency will be realized only if the degree of selectivity exceeds a threshold value S_0 . Accordingly, the employment of a spectrally-selective absorber coating will not be profitable unless its degree of selectivity is higher than the limit S_0 . The threshold value depends on the ratio R and the parameter N. At relatively-high values of N, it is more sensitive to R than to N.

6. NOMENCLATURE

A_{abs}	Absorber-surface area, m^2
A_{ap}	Aperture area, m^2
B	Dimensionless group defined in Eqn. (21)
C	Geometrical concentration ratio
D	Dimensionless group defined in Eqn. (22)
F	Merit function, defined by Eqn. (5)
G	Percentage gain in efficiency
I_D	Direct solar irradiance on aperture plane, W/m^2
N	Dimensionless parameter defined by Eqn. (15)
N_0	Value of N at which $G = 0$
R	Ratio of $\epsilon_{therm} / \epsilon$
S	Degree of selectivity defined by Eqn. (4)
S_0	Threshold value of S, given by Eqn. (23)
t_a	Ambient-air temperature, $^{\circ}C$
t_s	Average absorber-surface temperature, $^{\circ}C$
T_a	Ambient-air temperature, K
T_s	Average absorber-surface temperature, K
U_L	Overall collector heat-loss coefficient, $W/m^2.K$
α	Absorptance of non-selective absorber
α_{sol}	Absorptance for short-wave solar radiation
α_{therm}	Absorptance for long-wave thermal radiation
γ	Intercept factor of reflected radiation
ϵ	Emissivity of non-selective absorber

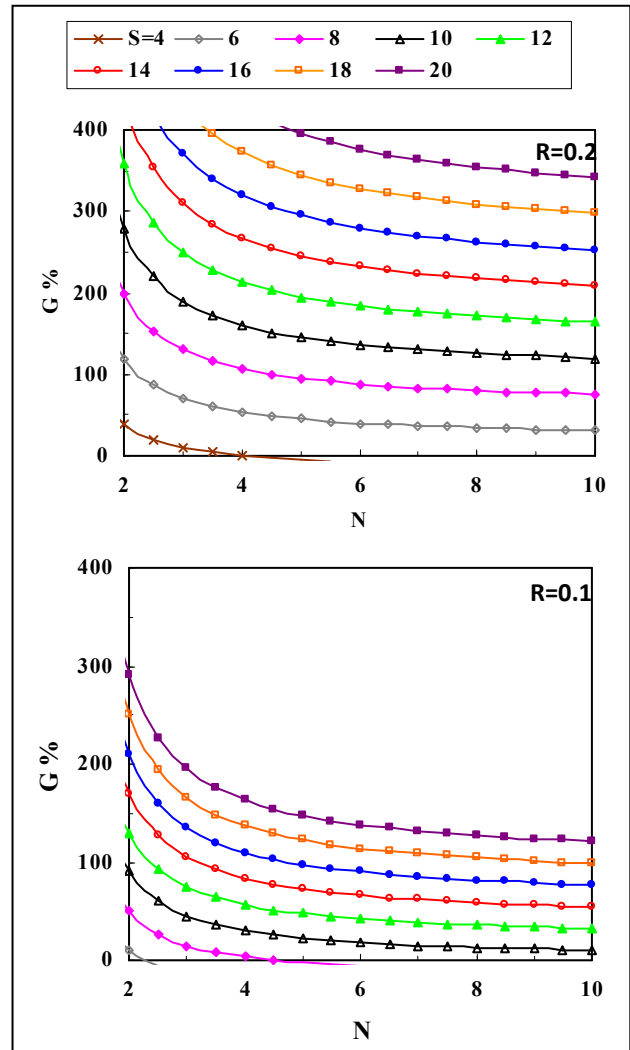


Fig. 9 Typical efficiency-gain values.

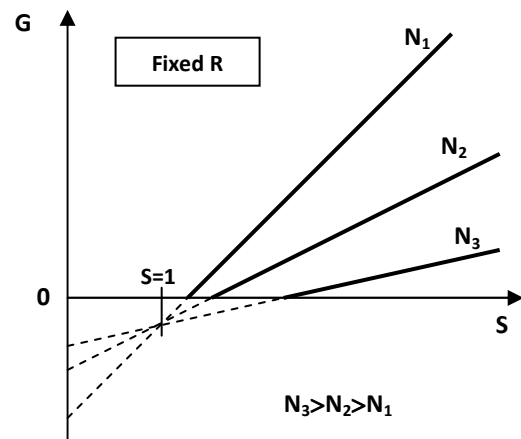


Fig. 10 Diagrammatic illustration of the variation of G with S.

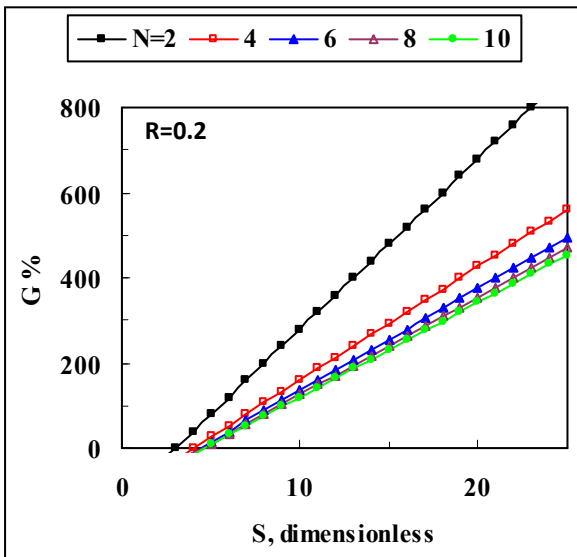


Fig. 11 Typical variation of G with S.

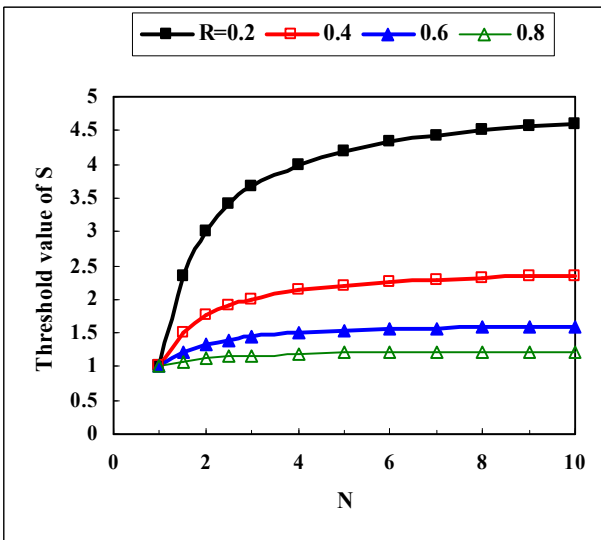


Fig. 12 Variation of S_0 with N and R.

ϵ_{therm}	Emissivity for thermal radiation
η	Efficiency of non-selective collector
η_{opt}	Optical efficiency
η_s	Efficiency of a selective collector
η_{therm}	Thermal efficiency of non-selective collector
λ	Wave length, μ
λ_c	Critical, or cut-off, wave length, μ
τ	Transmittance of glass cover
ρ	Reflectance of concentrator surface

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