INVESTIGATION OF THE EFFECTIVE TRANSMITTANCE-ABSORPTANCE PRODUCT OF SOLAR THERMAL COLLECTORS REGARDING RECENT IMPROVEMENTS OF GLAZING AND ABSORBER SPECTRAL PROPERTIES

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1. Introduction

A flat-plate collector in its simplest form consists of a flat heat exchanger with high absorptance for solar radiation (absorber) and a heat transport medium (air or water) to remove the heat from the heat exchanger. In this configuration, the absorber plate is directly exposed to surroundings. In order to reduce the thermal losses, not only are the back and sides thermally insulated with opaque materials (e.g. mineral wool), but a transparent cover can be placed between the absorber and the ambient air. On the one hand it reduces the amount of light reaching the absorber (optical losses due to the limited transmittance of the cover), but on the other hand, it reduces much of the convection losses from the front surface.

The optical properties of the transparent cover are characterized by the solar transmittance τ and the absorber properties by the solar absorptance α. The product of the cover transmittance τ with the absorber-plate absorptance α is called the transmittance-absorptance product. In a first approximation, the radiation absorbed by the absorber can be assumed to be the product of the incident radiation and the transmittance-absorptance product $(\tau\alpha)$.

$$\eta_{thermal} = F' \cdot \left((\tau\alpha) - U \cdot \frac{T_m - T_{amb}}{G} \right) \quad \text{(eq. 1)}$$

As multiple reflections occur between the glass cover and the absorber plate, this slightly increases the amount of radiation reaching the absorber plate (see Fig 1.)

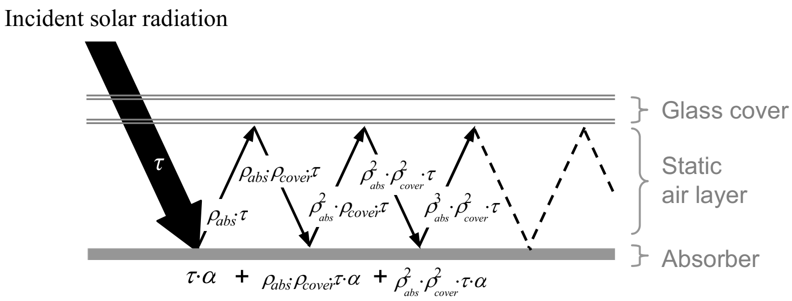


Fig. 1: Multiple reflections between collector transparent cover and the absorber plate. The angle of incidence represented in the figure is for illustration purposes only and is not taken into account in the presented calculation for near-normal incidence.

Therefore, an effective transmittance-absorptance product $(\tau\alpha)_{eff}$ has been introduced, which takes multiple reflections between the glass cover and the absorber plate into account. The importance of the effective transmittance-absorptance product is mainly given by the relation between the conversion factor η_0 of a solar collector and its collector efficiency factor F'

$$\eta_0 = F' \cdot (\tau\alpha)_{eff} \quad \text{(eq. 2)}$$

When a measured conversion factor η_0 and $(\tau\alpha)_{eff}$ are known, the collector efficiency factor F', which is an important value to assess a solar thermal absorber, can easily be calculated. The collector efficiency factor F' is an important measure for the assessment of the thermal efficiency of a solar absorber. It is the ratio of the heat transferred to the fluid to the heat generated on the absorber surface by absorbed solar radiation. It is important to be able to calculate F' correctly, independently of the absorber coating and the collector glazing.

An approximation valid for most solar collectors was given by Duffie and Beckman in 1980 (Duffie and Beckman, 1980). In their correlation, widely used in the solar thermal field, the effective transmittance-absorptance product is the product of transmittance and absorptance corrected by a factor of 1.01.

However, this correlation does not take into account the recent advances in the development of both glazing and absorber coating technologies. Nowadays, the transmittance of collector glazing can reach values above 0.94 due to the use of low-iron, "solar" glass and anti-reflective (AR) coatings. The absorptance of selectively coated solar absorber plates can be greater than 0.95, values which are much higher than in the 1980s.

This is the reason why the effective transmittance-absorptance product must be recalculated, taking into account the real multiple reflections occurring between the glass cover and the absorber plate.

2. Effective transmittance-absorptance product using experimental parameters

As presented in Figure 1, $(\tau\alpha)_{eff}$, the multiple reflections can be described as a geometric sequence.

$$(\tau\alpha)_{eff} = \tau \cdot \alpha \cdot \sum_{n=0}^{\infty} \left[\rho_{abs} \cdot \rho_{cover}\right]^n = \frac{\tau \cdot \alpha}{1 - \rho_{abs} \cdot \rho_{cover}} \quad \text{(eq. 3)}$$

In addition to the solar absorptance of the absorber α and the solar transmittance of the cover τ, this calculation requires two additional parameters, the solar reflection coefficients of both the absorber ρ_{abs} and the cover ρ_{cover}. Therefore, the effective transmittance-absorptance product has been calculated using experimental parameters measured on many absorbers and covers.

Table 1 lists both the solar transmittance and solar reflectance values of twelve different glass covers, six of AR-coated solar glass, four of standard solar (low-iron) glass without an AR coating and two of standard glass without an AR coating.

Tab. 1: Solar transmittance and solar reflectance of twelve different solar collector glass covers determined from spectral measurements according to EN 410.

Sample n°	Description	Transmittance (τ)	Reflectance (ρ_{cover})
Glass (1)	Standard	0.88	0.08
Glass (2)	Standard	0.89	0.09
Glass (3)	Low iron content	0.90	0.08
Glass (4)	Low iron content	0.90	0.08
Glass (5)	Low iron content	0.91	0.08
Glass (6)	Low iron content	0.91	0.08
Glass (7)	AR coating	0.92	0.06
Glass (8)	AR coating	0.93	0.05
Glass (9)	AR coating	0.94	0.05
Glass (10)	AR coating	0.94	0.04
Glass (11)	AR coating	0.94	0.04
Glass (12)	AR coating	0.96	0.03

In Table 2, both the solar reflectance and the solar absorptance values of fourteen different absorber types, eleven selectively coated absorbers, one black painted absorber, and two PV-Thermal absorbers using crystalline silicon solar cells.

Based on equation (3) and the integrated values presented in Tables 1 and 2, the transmittance-absorptance product and the effective transmittance-absorptance product have been calculated. To extract a clearer statement on the effect of the multiple reflection, we introduced a *Multi-Reflection Factor* (MRF). This factor is defined in equation (4) and is simply the ratio between the effective transmittance-absorptance product and the mathematical product of transmittance and absorptance.

$$MRF = \frac{(\tau\alpha)_{eff}}{\tau \cdot \alpha} \quad \text{(eq. 4)}$$

This factor was approximated to be around 1.01 by Duffie and Beckmann in 1980.

Tab. 2: Solar reflectance and solar absorptance of fourteen different absorber types, determined from spectral measurements in accordance with EN 410.

Sample n°	Description	Absorptance (α)	Reflectance ($r_{absorber}$)
Absorber (a)	PV-Thermal	0.92	0.08
Absorber (b)	Selective	0.92	0.08
Absorber (c)	Selective	0.93	0.07
Absorber (d)	Selective	0.93	0.07
Absorber(e)	PV-Thermal	0.93	0.07
Absorber (f)	Selective	0.93	0.07
Absorber (g)	Selective	0.93	0.07
Absorber(h)	Selective	0.94	0.06
Absorber (i)	Selective	0.94	0.06
Absorber(j)	Selective	0.95	0.05
Absorber (k)	Selective	0.95	0.05
Absorber (l)	Selective	0.95	0.05
Absorber (m)	Selective	0.96	0.04
Absorber (n)	Black painted	0.97	0.03

In Fig. 2.1, the Multi-Reflection Factor (MRF) is plotted as a function of both transmittance and absorptance. According to this graph obtained using the integrated parameters of both Tables 1 and 2, it seems to be clear that the Multi-Reflection Factor (MRF) value is strongly dependent on both plate absorptance and cover transmittance.

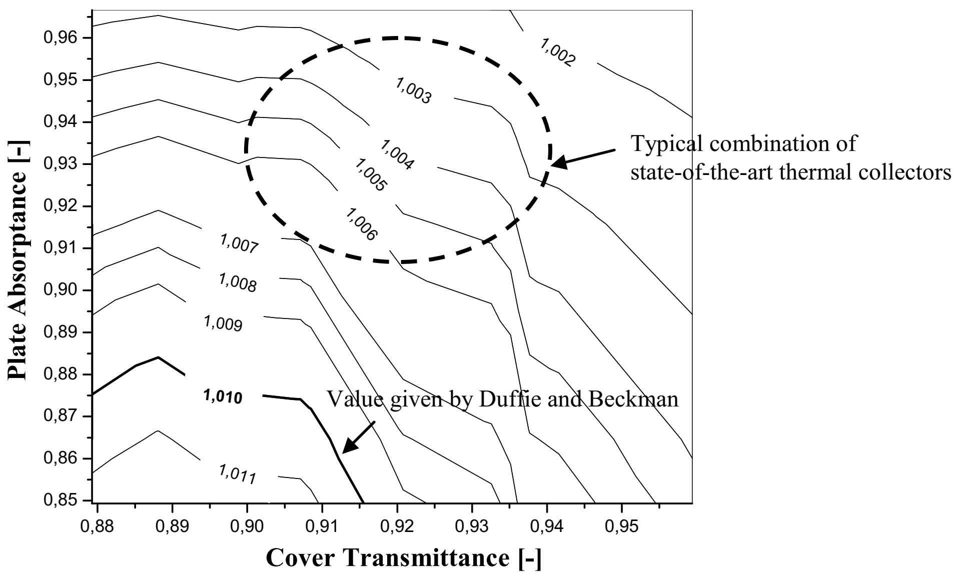


Fig. 2.1: Multi-Reflection Factor (MRF) as a function of both cover transmittance and plate absorptance.

In order to get a better overview of the dependence of the Multi-Reflection Factor (MRF) value on transmittance and absorptance, the Multi-Reflection Factor (MRF) is plotted in Figure 2.2 directly as a function of the transmittance-absorptance product. Values represented by a square correspond to the glass cover (1) to (6) (standard glass), values represented by a circle correspond to the glass covers (7) to (12) (AR coated glass). In this graph, the correlation given by Duffie and Beckman is also indicated.

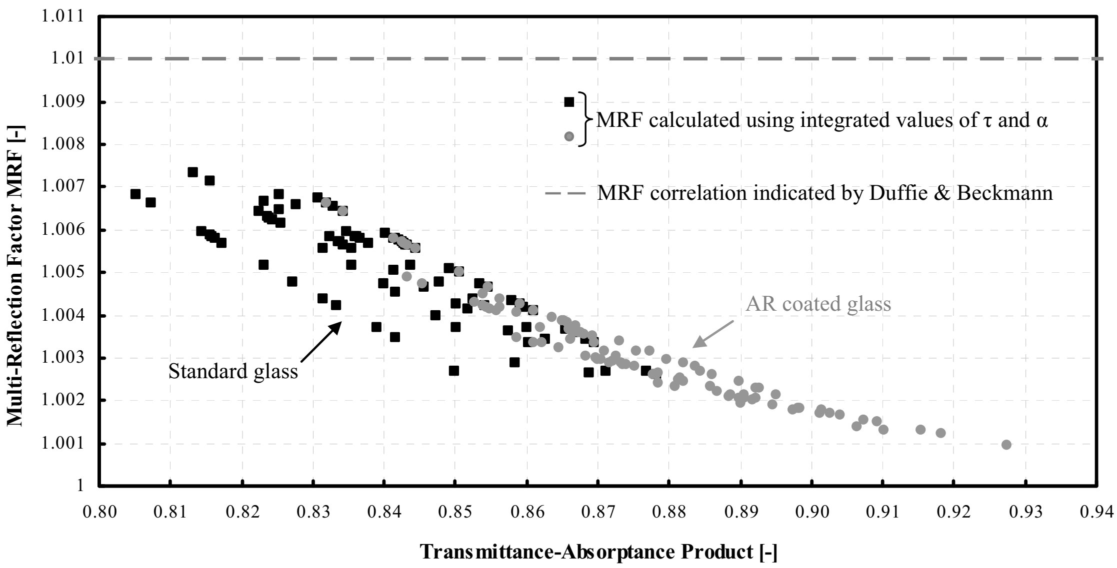


Fig. 2.2: Multi-Reflection Factor (MRF) as a function of the transmittance-absorptance product. Squares: values calculated for standard glass cover, circles: values calculated for AR coated glass cover. The correlation given by Duffie and Beckmann is also indicated in the graph.

The results presented in the Fig 2.2 show that the MRF values always stay below 1.008 for all combinations of the selected glass cover and absorber plate properties. It is interesting to note that the values obtained for AR coated glass covers seem to have a much closer correlation (circles) than the values obtained for standard glass covers (square).

3. Effective transmittance-absorptance product using spectral measurements

The parameters presented in Tables 1 and 2 are integrated parameters regarding the solar spectra. Since the spectral dependence of both the cover and the absorber plate may have an impact on the Multi-Reflection Factor, the effective transmittance-absorptance product has also been calculated using the spectral data measured on these many absorbers and covers, in order to obtain higher accuracy.

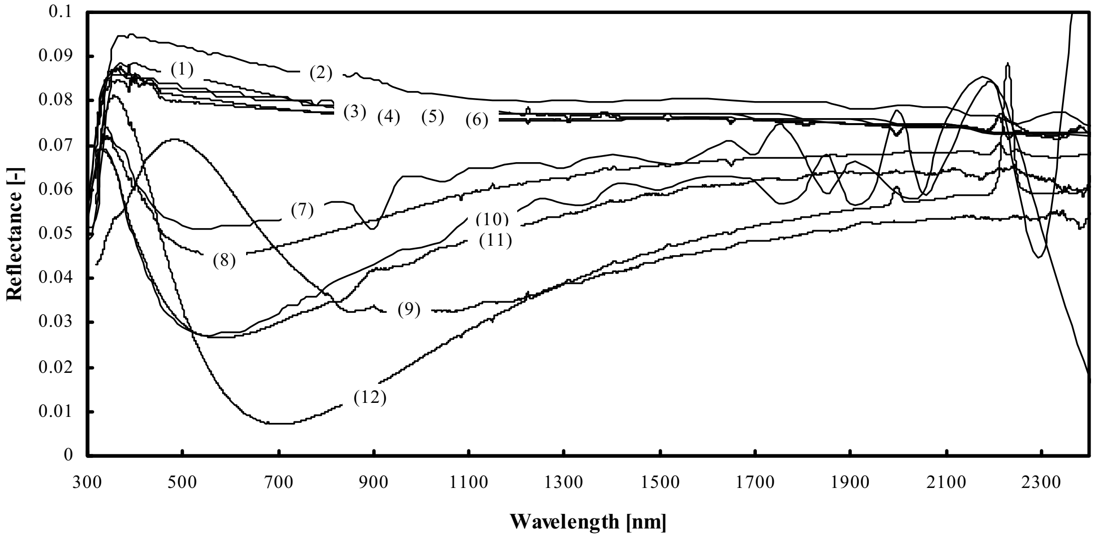
The transmittance and reflectance spectra for the glass cover panes came from two sources, the publicly accessible International Glazing Data Base maintained by Lawrence Berkeley National Laboratory [LBNL] and measurements made by the accredited “TestLab Solar Façades” at Fraunhofer ISE. These measurements were made with laboratory-grade spectrophotometers and have been checked for internal consistency. The reflectance spectra for the absorber plates were carried out at Fraunhofer ISE as internal measurements.

In Fig. 3.1, the range of spectra for the reflectance (top) and the transmittance (bottom) of the twelve glass covers mentioned in the Table 1 (AR coated, solar glass, standard glass) is presented.

In Fig. 3.2, the range of spectra for the reflectance of the sixteen absorber plate mentioned in Table 2 (selectively coated, black painted and PV-Thermal) is presented.

Based on these spectral measurements and on equation (5), the transmittance-absorptance product spectra and the effective transmittance-absorptance product spectra have been calculated and then integrated.

$$(\tau\alpha)_{eff} = \int_\lambda \left[\tau(\lambda)\cdot(1-\rho_{abs}(\lambda))\cdot \sum_{n=0}^{\infty} \left[\rho_{abs}(\lambda)\cdot \rho_{cover}(\lambda)\right]^n \right]\cdot d\lambda = \int_\lambda \left[\frac{\tau(\lambda)\cdot(1-\rho_{abs}(\lambda))}{1-\rho_{abs}(\lambda)\cdot \rho_{cover}(\lambda)} \right]\cdot d\lambda \quad \text{(eq. 5)}$$



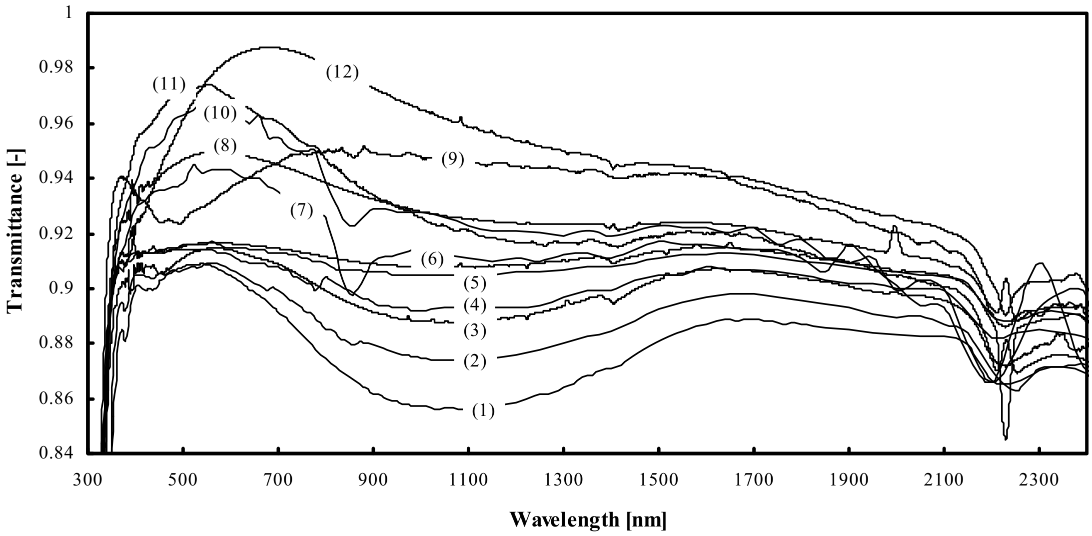


Fig. 3.1: Measured reflectance (up) and transmittance (down) spectra on several types of solar collector glass covers.

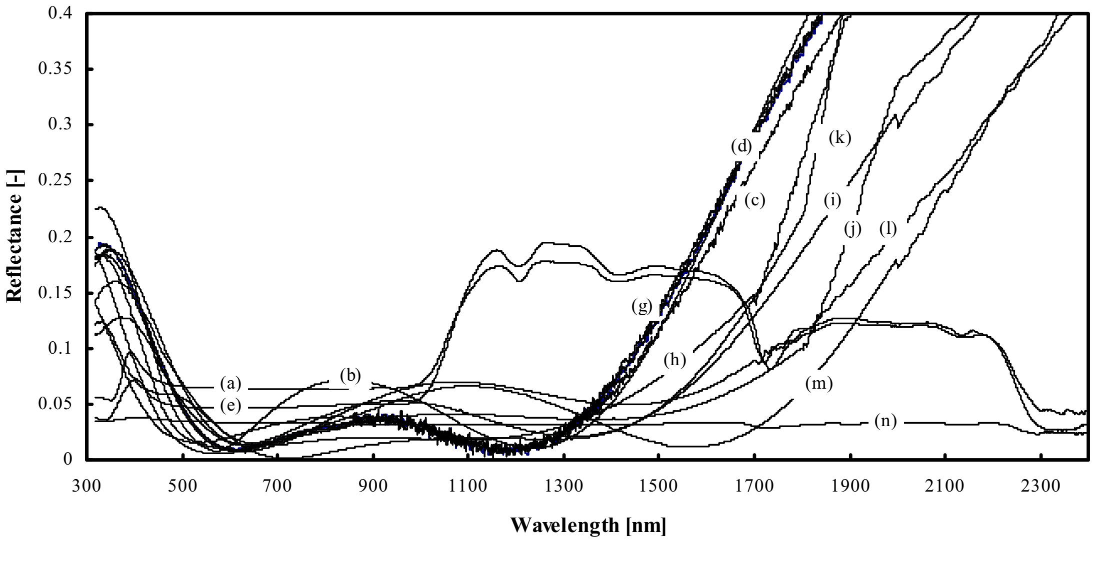


Fig. 3.2: Measured reflectance spectra for several types of thermal absorber.

In Fig. 3.3, the Multi-Reflection Factor (MRF) obtained using the spectral measurements is plotted as a function of the transmittance-absorptance product and compared to the Multi-Reflection Factor (MRF) obtained in the previous part using the product of integrated values. The results of the broadband and spectral calculations are compared to the correlation of Duffie and Beckmann.

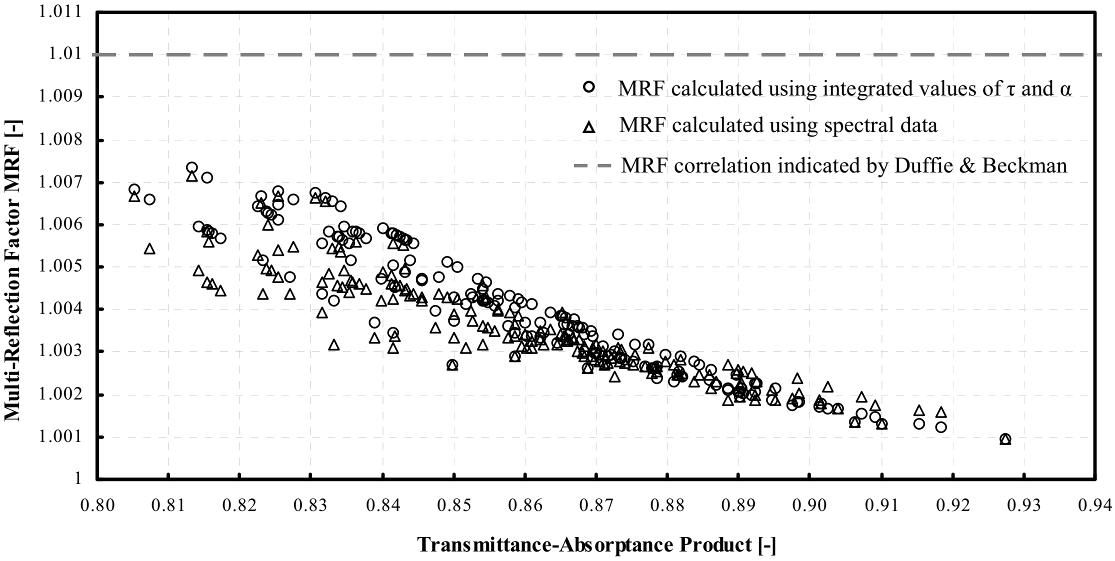


Fig. 3.3: Multi-Reflection Factor (MRF) calculated using both integrated parameters and spectral data as a function of the transmittance-absorptance product based on integrated parameters and spectral data respectively. The correlation given by Duffie and Beckmann is also indicated in the graph.

The results presented in Fig 3.3 show that for the selected glazing samples and absorbers, the spectrally calculated MRF values also always remain below 1.008 for all combinations of glass cover and absorber plate properties.

The values calculated using the spectral data differ slightly from those calculated previously using integrated parameters but the difference is within the tolerance resulting from measurement uncertainty. To summarize, the results show that for state-of-the-art glazing and absorbers, the correlation of Duffie and Beckman overestimates the multiple reflections and thus underestimates the collector efficiency factor *F'* calculated from η_0. Therefore, it no longer corresponds to the current situation and must be adapted to account for recent improvement of glazing and collector properties.

In fact, for the combination of an absorber with high solar absorptance with an AR-coated glass cover, the Multi-Reflection Factor, calculated either with integrated parameters or spectral data approaches 1 and therefore could be neglected in a first approximation.

In order to reach good accuracy, especially regarding the calculation of the collector efficiency factor *F'*, we suggest that the information regarding the glass cover properties should not be restricted only to the transmittance. The reflectance should also be specified in each case so that the real transmittance-absorptance product can be calculated. Since there is no significant difference between for calculations based on spectral and integrated data, the information regarding the glass properties can be restricted to the integrated parameters.

However, in the case where the reflectance of the glass cover is not known, an empirical correlation can be also used. In Fig 3.4 the effective transmittance-absorptance product $(\tau\alpha)_{eff}$ is plotted as a function of the transmittance-absorptance product $(\tau\alpha)$. Since the correlation between $(\tau\alpha)_{eff}$ and $(\tau\alpha)$ can be approximated using a linear fit with a very good correlation, the following equation can be used for $\alpha > 0.90$ and $\tau > 0.90$ if the reflectance of the glass is not known.

$$(\tau\alpha)_{eff} = 0.95 \cdot \tau \cdot \alpha + 0.043 \quad \text{(eq. 6)}$$

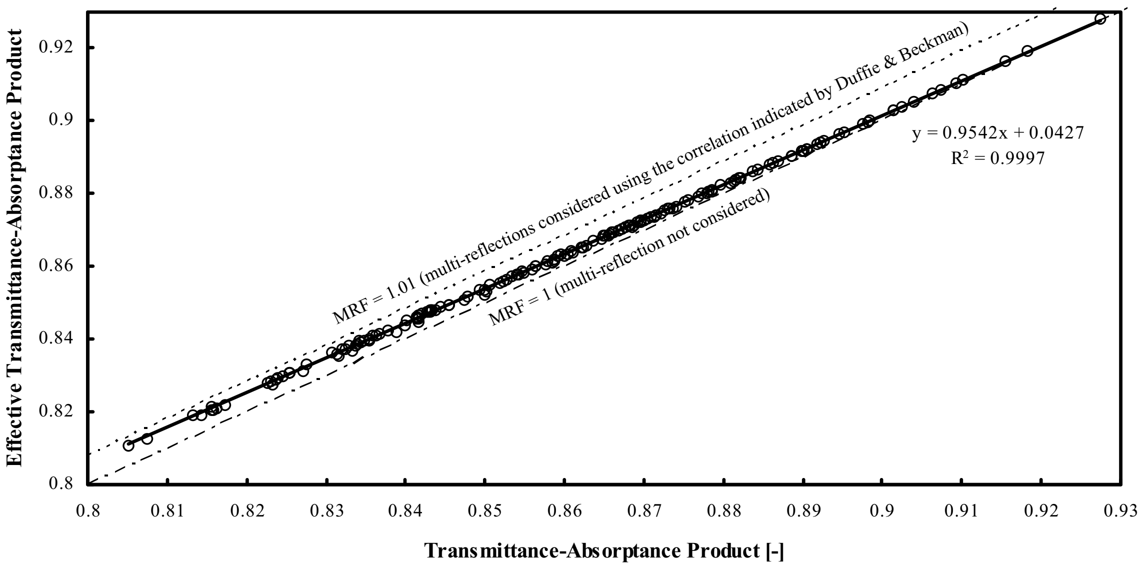


Fig. 3.4: Effective transmittance-absorptance product as a function of the transmittance-absorptance product for state-of-the-art glazing and absorbers.

4. Conclusion

In this paper a general Multi-Reflection Factor (MRF) has been introduced as the ratio between the effective transmittance-absorptance product and the mathematical product of transmittance and absorptance. In the first part of this paper, the Multi-Reflection Factor has been calculated using integrated parameters determined for many absorbers (selective and non-selective) and covers (AR coated, solar glass, standard glass). Then, in the second part, the Multi-Reflection Factor has been calculated using spectral data for the same absorbers and covers in order to reach higher accuracy. The results of broadband and spectral calculation have been compared to the correlation of Duffie and Beckman.

The results show that for many state-of-the-art glazing types and absorbers, the value MRF = 1.01 established by Duffie and Beckman in 1980 is no longer valid. This correlation does not take recent advances in the development of both glazing and absorber coating technologies into account, and thus overestimates the effect of multiple reflections and underestimates the collector efficiency factor *F´*. This means that for a given (measured) conversion factor η_0, the calculated collector efficiency factor *F’* will be higher. For an absorber-glazing combination with MRF ≈ 1, the real collector efficiency factor *F’* would be up to 1 % higher than if it were calculated according to Duffie and Beckman.

For a correct estimation of the Multi-Reflection Factor, the cover transmittance, the absorptance of the absorber plate but also the reflectance of the glass cover are required. The integrated value over the solar spectrum of those three parameters should however, be sufficient to reach good accuracy due to the good correlation between the Multi-Reflection Factor calculated using spectral data and integrated values over the solar spectrum and presented in the paper. In the case where the reflectance is an unknown parameter, as is often the case, an empirical correlation can be used. This new correlation was obtained using the measurements and calculation and is presented in the paper. It could become an alternative to the correlation of Duffie and Beckman in the future.

5. References

Duffie and Beckmann, 1980. Duffie, J.A., Beckman, W.A., 1980, Solar Engineering of Thermal Processes, John Wiley & Sons Inc, New York.