



PERGAMON

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

SCIENCE @ DIRECT®

Renewable Energy 28 (2003) 887–900

RENEWABLE  
ENERGY

[www.elsevier.com/locate/renene](http://www.elsevier.com/locate/renene)

# The total infrared transmittance of polymerised vinyl fluoride films for a wide range of radiant source temperature

P.T. Tsilingiris

*Department of Energy Engineering, Technological Education Institution (TEI) of Athens, A. Spyridonos str. GR 122 10, Egaleo, Athens, Greece*

Received 30 June 2002; accepted 24 July 2002

---

## Abstract

The current growing interest on the use of polymer films is mainly attributed to their suitability as glazing and construction materials in various fields of contemporary technology. Polymerised vinyl fluoride (Tedlar) films are nowadays considered as very suitable for construction and energy applications. Most polymer films are partly transparent, showing a strongly selective absorbing behaviour at the infrared spectrum. Their total hemispherical infrared transmittance which depends on radiant source temperature and film thickness, is a very useful fundamental property for energy balance and heat transfer calculations. However it is not always possible to locate information about this property in the literature. In the present investigation the calculation of the total infrared transmittance of Tedlar films is presented, based on recent spectral transmittance measurements of commercial tedlar films for the wavelength band between 2.5–42.5  $\mu\text{m}$  and for a broad range of radiant source temperatures between –20 to 500 C. Results from the present analysis were found to be in reasonable agreement with earlier data, derived for a specific film thickness and for a narrow range of radiant source temperatures by Willier.

© 2002 Elsevier Science Ltd. All rights reserved.

*Keywords:* Polymer film transmittance; Tedlar Infrared transmittance; Solar collector glazings

---

## 1. Introduction

The investigation of radiative properties of thin solid films had been the subject of substantial theoretical and applied research over the past few decades [1,2], owing to their considerable practical importance in optical and photovoltaic components. However, remarkably less attention has been devoted to the investigation of optical

### Nomenclature

b	Film thickness (m);
I	Radiation intensity ( $\text{W}\cdot\text{m}^{-2}$ );
n	Refractive index (-);
<i>n</i>	Complex refractive index;
Q	Correction factor (-);
r	Reflection loss coefficient (-);
wn	Wavenumber ( $\text{cm}^{-1}$ );
x	Optical path length (m);

### Subscripts

a	Air;
b	Film thickness;
f	Film;
$\lambda$	Wavelength;

### Greek Letters

$\alpha$	Absorption coefficient ( $\text{m}^{-1}$ );
$\theta$	Angle of incidence;
$\kappa$	Electromagnetic extinction coefficient (-);
$\lambda$	Wavelength (m);
$\tau$	Transmission coefficient (-);
$\varphi$	Refraction angle.

and radiative properties of polymer films, which are crucial for a broad range of modern engineering applications.

In the field of radiative cooling technology, where polymer films are being employed as convection suppressing windscreens to the radiative surfaces, their fundamental characteristic of partial infrared transmission is being employed for the radiative heat exchange with clear night skies through the atmospheric transmittance window. The development of a radiative heat exchange analysis, aiming at the cooling performance of the radiative panels, is based on an accurate prediction of the total infrared transmission as a function of the film thickness and radiant source temperature.

Previous investigations on the derivation of the collector loss coefficients for collector glazings involving polymer films by Hollands and Wright [3] and the performance of radiant panels with convection suppression polymer film covers by Jannot and Coulibaly [4], have been based on assuming a fixed average estimated value of total hemispherical transmittance of polymer films over a broad wavelength range. Wijesundera and Iqbal [5], investigated the effect of an upper plastic film thickness on the collector top loss coefficient. For the purpose of their heat transfer calculations Edwards and Rhee [6], have calculated the total Teflon film transmittance using spectral data previously reported in the literature. Although the calculation details

are completely lacking, total transmittance values around 20% were reported for a 0.1 mm teflon film.

The assumption of using a selective absorber with a step emissivity behaviour at the transmittance window of the film may strongly simplify the situation, allowing the elimination of the calculation of the hemispherical normal broadband IR transmission of polymer films. An absorber of this kind with a strong step absorptivity behaviour within the narrow atmospheric transmittance window between 8–13  $\mu\text{m}$  was employed for example by Catalanotti et al. [7], who for the purpose of his analysis was simply assigned a fixed transmittance value for the specifically employed polyethylene film, based on the average value of three IR spectral transmittance measurements, corresponding to the edge and midpoint wavelengths of the transmittance window. Although this procedure is not strictly valid for other than strong selective absorbers, such an estimated polyethylene transmittance was also employed as a first order approach in subsequent investigations [8], involving ordinary gray absorbers, owing to the lack of more suitable data.

The radiation spectrum of most polymers contains a large number of resonances in the near and far IR parts of the electromagnetic spectrum. This is attributed to the molecular structure of most polymers which is fundamentally composed of randomly oriented, long-chained polymeric molecules, the excitation of radical bonds of which usually causes a large number of sharp resonances.

Willier [9], was the first who estimated the total transmittance of the earlier type 20, 0.1 mm Tedlar film for a relatively narrow temperature range of the blackbody source temperatures between 0 and 200 °C, using spectral extinction data for the earlier developed film over the limited IR wavelength band between 2–16  $\mu\text{m}$ . The aim of his original investigation was the performance prediction of solar collectors using Tedlar films instead of glass panes as a glazing material. Although extensive details of his analysis are not available from his original manuscript, it appears that these earlier calculations were based on graphical integration using cumulative black body radiation tables under the assumption of the Beer's exponential attenuation law. However, the insufficient data combined with the inadequate procedures then employed, leads to rather limited confidence on the results of this earlier analysis aiming at the evaluation of the total IR transmittance of the specific 0.1 mm thickness Tedlar film.

To avoid the inconvenience of handling sharply varying spectral absorption data, an alternative simple approximate technique has been proposed by Tien et al. [10], based on the derivation of band averaged optical constants similar to the approach adopted by subsequent investigators [11,12], for the calculation of total transmission through a liquid water layer which also behaves as a strongly selective absorber.

## **2. The potential of polymer films in contemporary technology**

The use of polymer films as glazing materials appear currently to expand in the modern architectural design, horticulture, greenhouse construction and other engineering or higher temperature industrial applications. Although glass is still considered

to be a traditional structural and construction material of indisputable qualities, certain polymer films appear to possess the potential to compete with glass in many aspects of contemporary technology.

The idea of using plastic films to replace glass in certain technological fields is not new. Numerous polymer films with specific qualities were developed and manufactured under various trade names during the past decades, like Mylar (Polyesters), Kapton (Polyamide) and Tensiltarp (Polyethylene). Among them the Polymerised vinyl fluoride films (Tedlar) were proposed a few decades ago by Edlin [13,14], for use as top or inner glazing materials in solar collectors, especially when fragility, weight and cost considerations dominate.

Although this material was first developed in the early 1940s as a result of the extensive fluorocarbon research program, it took almost two decades of field ageing testing to confirm its qualities and advanced properties, which led to the first commercial production of Tedlar films almost 40 years ago by Dupont.

During the last few decades a variety of ageing tests in pilot building and solar collector glazing systems for the earlier and subsequent improved types of Tedlar films under the designation numbers 20 and 400BG20TR respectively, allowed the continuous improvement of chemical composition and a growing confidence in these films. This improvement has led to the development of the latest improved film designated as 400BG20SE which was developed specifically for solar energy technology.

Although this low-cost material may not yet compete with glass as regards its undisputable superior spectral qualities (glass is non weatherable, completely opaque in the IR spectrum material), it would be quite suitable as inner or even outer glazing where large size, lightweight, in situ assembled design of solar collector arrays is important. As soon as at least a five year confidence against ageing for low temperature applications is securely established, the material may possibly begin to replace glass from usual building construction or solar energy applications, especially for volume production of solar collectors.

Polymers are already considered not only potential glazing materials but also suitable as low cost, all plastic modular mass production solar water heaters and associated components [15,16].

### 3. The analysis of radiation absorption in polymer films

The extinction of electromagnetic radiation in imperfect dielectrics is characterised by the so called complex refractive index, the real and imaginary parts of which are the refractive index and extinction coefficient of the material,

$$\mathbf{n} = n - j\kappa \quad (1)$$

Certain polymer films appear to have a slightly cloudy appearance. This is attributed to their heterogeneous structure with usually coexisting ordered and disordered domains of macromolecules, which causes scattering phenomena that are not always simple to predict. When a monochromatic beam of intensity  $I_0(\lambda, \theta)$  propagates at

the direction  $\theta$  in a partially absorbing and negligibly scattering medium, it undergoes attenuation according to Beer's law which is proportional to its optical path length  $x$ ,

$$I_x(\lambda, \theta) = I_0(\lambda, \theta) \cdot \exp(-\alpha_\lambda \cdot x) \tag{2}$$

where  $\alpha_\lambda$  is the spectral absorption coefficient which is given according to the electromagnetic theory (Siegel and Howell [17]) by the expression,

$$\alpha_\lambda = 4\pi \cdot \kappa / \lambda \tag{3}$$

When the beam is incident at the surface of a polymer film at an incidence angle  $\theta$ , a fraction of  $I_0(\lambda, \theta) \cdot r(\theta)$  is reflected, where  $r(\theta)$  is the Fresnell reflection loss coefficient at the polymer-air interface. The remaining radiation intensity just crossing the interface which is  $[1 - r(\theta)] \cdot I_0(\lambda, \theta)$ , will propagate through the material and will suffer an exponential attenuation according to Beer's law. The radiation intensity just before crossing the second polymer-air interface will be  $[1 - r(\theta)] \cdot I_0(\lambda, \theta) \cdot \exp[-\alpha_\lambda \cdot x]$  and the emerging intensity will become  $[1 - r(\theta)]^2 \cdot I_0(\lambda, \theta) \cdot \exp[-\alpha_\lambda \cdot x]$ , as a result of a second reflection loss at the polymer-air interface.

The transmitted intensity as shown in Fig. 1, is the contribution of all multiple

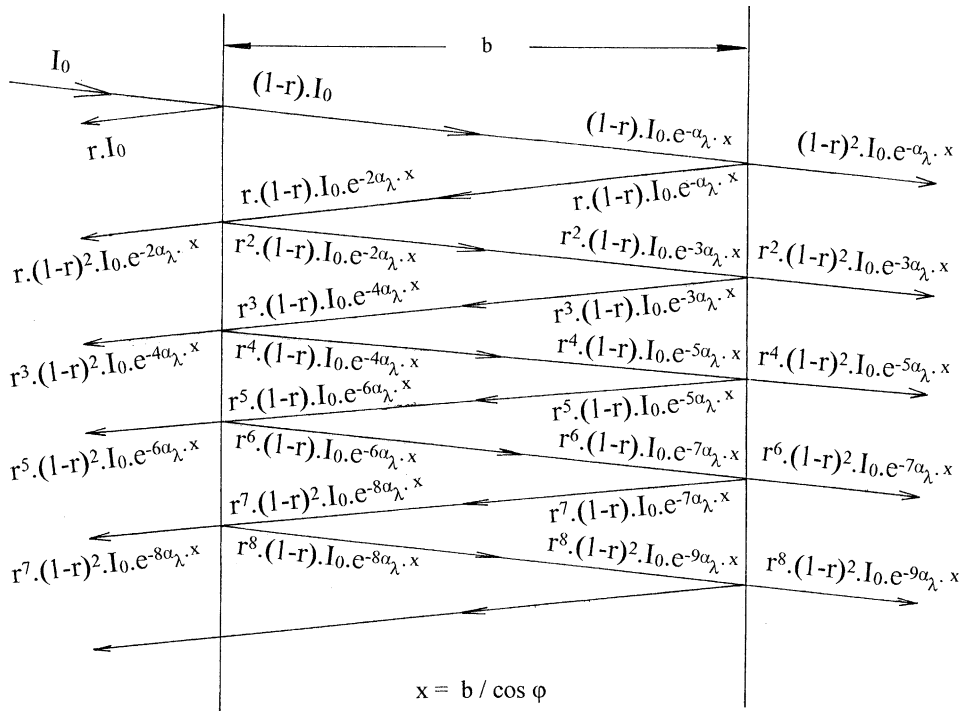


Fig. 1. The full account of radiant energy flow components in a system allowing multiple internal reflections with reference to a constant thickness polymer film.

transmission components and it is calculated as the summation of their infinite series by the expression,

$$I_x(\lambda, \theta) = \frac{[1-r(\theta)]^2 \cdot I_0(\lambda, \theta)}{1-r(\theta)^2 \cdot \exp[-2\alpha_\lambda \cdot x]} \cdot \exp[-\alpha_\lambda x] \quad (4)$$

Assuming that the film thickness is  $b$ , the expression (4) becomes

$$I_b(\lambda, \theta) = [1-r(\theta)]^2 \cdot I_0(\lambda, \theta) \cdot [1-r(\theta)^2 \cdot \exp[-2\alpha_\lambda b / \cos\varphi(\theta)]]^{-1} \cdot \exp[-\alpha_\lambda \cdot b / \cos\varphi(\theta)] \quad (5)$$

where  $\varphi(\theta)$  is the refraction angle which is assumed to satisfy Snell's law,

$$\varphi = \arcsin[(1/n_f) \cdot \sin\theta] \quad (6)$$

Lodenquai [18], suggested that the transmission expression (5) should be corrected by the introduction of the extra multiplicative factor  $Q_f$  arising from the complex nature of the refractive index of the partially conducting polymer film, which is expressed as

$$Q_f = [re(\mathbf{n}_a/n_f) \cdot re(\mathbf{n}_f/n_a)]^{-1} \quad (7)$$

where  $\mathbf{n}_a$  and  $\mathbf{n}_f$  the complex refractive indices of air and polymer film respectively. Assuming that air can be clearly considered as a perfect dielectric material with a complex refractive index of  $\mathbf{n}_a = 1$ , while the complex refractive index of the polymer film material is expressed in terms of its real and imaginary parts,

$$\mathbf{n}_f = n_f - jk_f$$

it can easily be derived that,

$$Q_f = 1 + (\alpha_\lambda \cdot \lambda / 4\pi n_f)^2 \quad (8)$$

Numerical values of  $n_f$  which are usually available from the literature, refer almost always to the fixed wavelength of the sodium  $D$  line at  $\lambda = 0.58932 \mu\text{m}$  as a result of Abbe refractometry measurements. According to reported data from Edlin [19], it would be reasonable to assume an average value of  $n_f = 1.425$  for Tedlar corresponding to the wavelength region between near and far IR.

An inspection of the calculated absorption coefficient data for the polymer film under consideration in Fig. 2 suggests maximum values lower than about  $50000 \text{ m}^{-1}$  for wavelengths around  $12 \mu\text{m}$ , which for  $n_f = 1.425$  leads to an estimated numerical value of the quantity  $(Q_f - 1)$  is around  $10^{-3}$ . Since the measurement as well as graphical compilation errors are considered to be in the order of  $10^{-2}$ , the effect of the corrective factor for the practical polymer film thicknesses becomes negligible.

The expression (5) for normal incidence becomes,

$$I_b(\lambda, 0) = [1-r(0)]^2 \cdot [1-r(0)^2 \cdot \exp[-2\alpha_\lambda b]]^{-1} \cdot I_0(\lambda, 0) \cdot \exp(-\alpha_\lambda \cdot b) \quad (9)$$

The Fresnell reflection coefficient at the air-polymer interface is determined by the refractive index of polymer material, which for normal incidence is

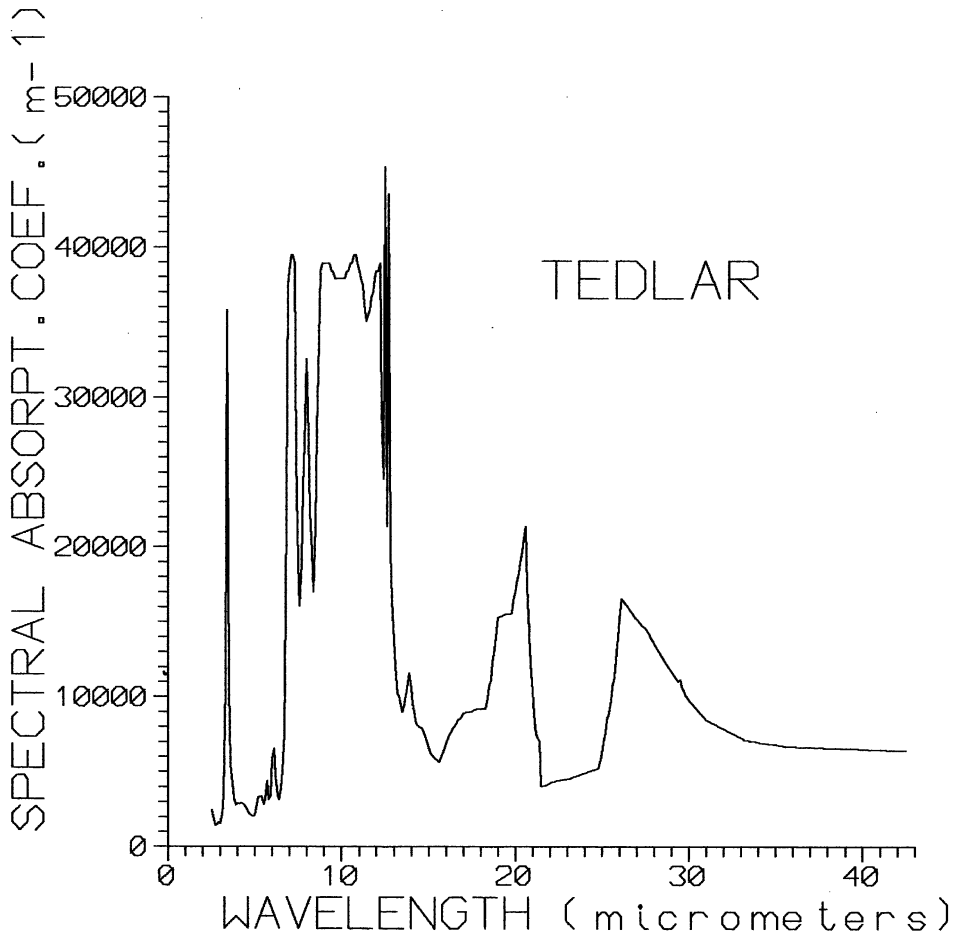


Fig. 2. The calculated spectral absorption coefficient of the type 400SE tedlar film which was employed for the evaluation of total film transmission through the expression (15) in the wavelength band between 2.5-42.5  $\mu\text{m}$ .

$$r(0) = [(n_f - 1)^2 + \kappa_f^2] / [(n_f + 1)^2 + \kappa_f^2] \tag{10}$$

which for  $n_f \gg \kappa_f$ , as happens in polymer films becomes,

$$r(0) = [(n_f - 1) / (n_f + 1)]^2 \tag{11}$$

For  $n_f = 1.425$ , the estimated reflection loss coefficient as derived from (11) is about  $r(0) = 0.030$ , something which leads to  $r(0)^2 \cdot \exp[-2\alpha_\lambda \cdot b] \ll 1$  for all practical film thicknesses and therefore the expression (9) becomes,

$$I_b(\lambda, 0) = [1 - r(0)]^2 \cdot I_0(\lambda, 0) \cdot \exp[-\alpha_\lambda \cdot b] \tag{12}$$

As soon as the spectral absorption and normal incidence reflection loss coefficients

are available, it is possible to calculate the total transmitted energy through a polymer film of a given thickness  $b$  by the expression,

$$I_b = [1 - r(0)]^2 \cdot \int_{\lambda_{\min}}^{\lambda_{\max}} I_0(\lambda, 0) \cdot \exp[-\alpha_{\lambda} \cdot b] d\lambda \quad (13)$$

where  $I_0(\lambda, 0)$  the normally incident monochromatic radiation intensity from a gray body and  $\lambda_{\min}$ ,  $\lambda_{\max}$  are the boundaries of the wavelength range under consideration.

Since the total transmission is defined as the ratio  $\tau_b = I_b/I_0$ , it is calculated by the expression,

$$\tau_b = [1 - r(0)]^2 \cdot \int_{\lambda_{\min}}^{\lambda_{\max}} I_0(\lambda, 0) \cdot \exp[-\alpha_{\lambda} \cdot b] d\lambda / \int_{\lambda_{\min}}^{\lambda_{\max}} I_0(\lambda, 0) d\lambda \quad (14)$$

where  $I_0$  is the total incident energy at the polymer film surface.

#### 4. Results and discussion

For the calculation of the total film transmittance at a certain blackbody temperature according to the expression (14) it is necessary to rely on spectral absorption coefficient data  $\alpha_{\lambda}$ , of sufficient wavelength resolution. It would be possibly convenient to obtain these data from existing values of the imaginary part of the refractive index. However since such data are usually lacking, it would be obvious that their calculation should be carried out by the following expression

$$\alpha_{\lambda} = [2\ln[1 - r(0)] - \ln\tau(\lambda, 0)] / b \quad (15)$$

using measured normal incidence spectral transmission data  $\tau(\lambda, 0)$ , of an adequate wavelength resolution over a sufficiently wide wavelength range and the estimated values of the normal incidence reflection loss coefficient  $r(0)$ . Such data can be derived using a suitable near and far IR radiation spectrophotometer, involving a flat response detector and an intergrating sphere to allow measurement of forward scattered radiation.

Unfortunately spectral transmission data corresponding to a relatively wide IR spectrum are usually scarce, and one has to rely on relatively narrow band data or incomplete measurements, of sometimes questionable reliability which sporadically appear in the literature.

For the purpose of the present analysis it was found that the most reliable data are those published for the latest type 0.1 mm Tedlar film under the designation number 400BG20SE PVF by DuPont [20], which are available from the manufacturers technical specification sheets. They are presented in the form of spectral transmission graphs, where the measured transmission is plotted against the wavenumber  $wn(\text{cm}^{-1})$ , where  $wn = (100/\lambda)^{-1}$  for an appreciably wide wavelength range corre-



sponding to between about 2 up to 40  $\mu\text{m}$ . After scanning and compilation of these data, a linear axes spectral transmittance plot was drawn as a function of wavelength in the range between 2.5–42.5  $\mu\text{m}$  as shown in Fig. 2. In this plot the various resonance bands and transmission windows are shown, among which the 13–18  $\mu\text{m}$ , 21–25  $\mu\text{m}$ , 33–40  $\mu\text{m}$  and especially the 2–6  $\mu\text{m}$  predominate.

These data were employed for the evaluation of the spectral absorption coefficient  $\alpha_\lambda$  which was calculated for the specified film thickness and the normal incidence reflection loss coefficient  $r(0)$  throughout the expression (14). It is obvious that the so calculated transmittance corresponds to new films, since the environmental exposure causes ageing, which leads to a subsequent increase of the measured spectral absorption coefficient data and reduction of the total infrared transmittance. The calculated approximately 400 spectral absorption coefficient values with a wavelength resolution of 0.1  $\mu\text{m}$  were stored in a data file and plotted in the Fig. 3, in

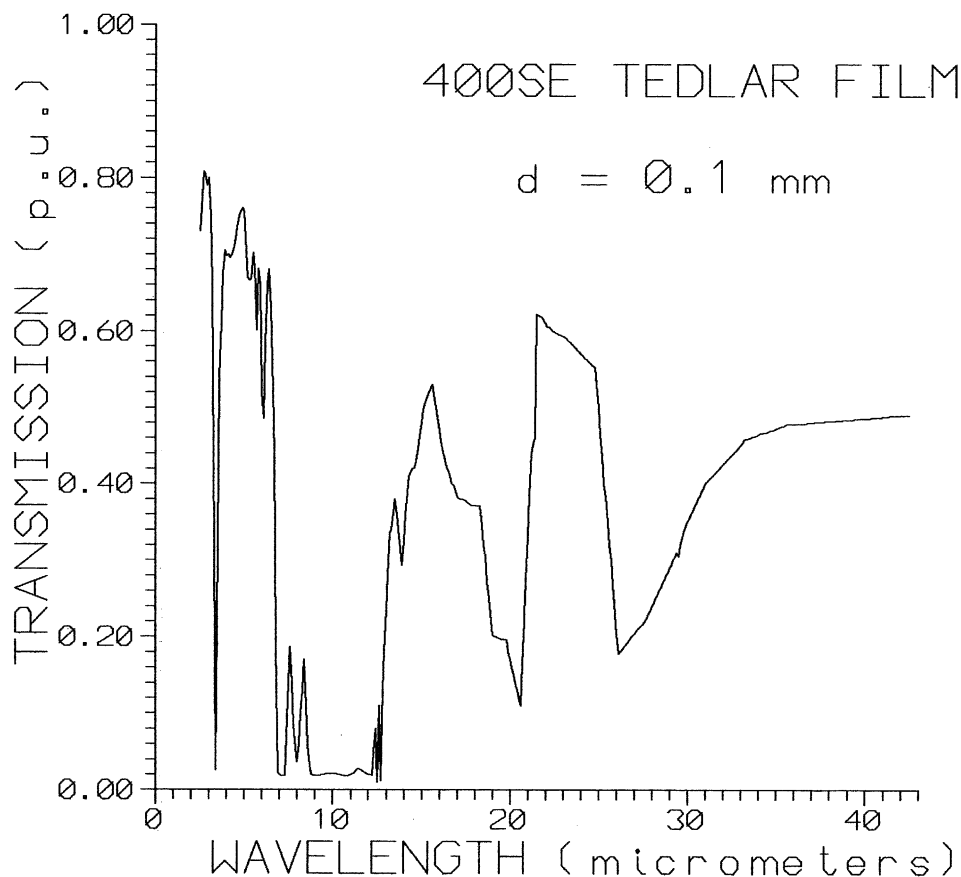


Fig. 3. The measured spectral transmission coefficient in linear and uniform coordinates as compiled from wavenumber coordinate plots for the 0.1 mm (4 mil) type 400SE tedlar film.

which the highest values of about  $40,000 \text{ m}^{-1}$  are shown to lie in the wavelength region between about 7 and 12  $\mu\text{m}$ .

The numerical value of the total film transmittance at a fixed radiant source temperature which is given by the expression (14), clearly depends on the specified integration limits. Most polymer films, although appearing to be highly transparent up to about 2  $\mu\text{m}$ , begin to absorb strongly at longer wavelengths. For this reason this wavelength usually marks the shortest wavelength boundary  $\lambda_{\min}$ , within the wavelength region, where the first strong near IR resonance occurs.

However, the selection of the longest wavelength boundary  $\lambda_{\max}$  is always practically determined by the longest wavelength of the spectral absorption data available for the material under consideration. For this reason the calculated total transmission by (14) may possibly differ from the values predicted by the same expression when  $\lambda_{\max} \rightarrow \infty$ , especially for very low blackbody temperatures. This is attributed to the fact that there will probably be a substantial fraction of blackbody energy at longer than  $\lambda_{\max}$  wavelengths, where spectral absorption data are unavailable.

Therefore a reasonable accuracy is expected for those blackbody temperatures, for which practically almost all the blackbody energy is distributed within the wavelength band between  $\lambda_{\min}$  and  $\lambda_{\max}$ .

Let  $F$  and  $F'$  be the fractions of total blackbody emission in the wavelength band between  $0-\lambda_{\min} = 2.5 \mu\text{m}$  and  $0-\lambda_{\max} = 42.5 \mu\text{m}$  respectively, which are calculated from blackbody radiation functions in relationship to the blackbody temperature.

According to the Wien's displacement law for fixed  $\lambda_{\min}$  and  $\lambda_{\max}$ , both  $F$  and  $F'$  are proportional to the blackbody temperature. This is shown in Fig. 4 in which fractions  $F'$  and  $1 - F$  are plotted as a function of blackbody temperature. The blackbody energy contained within the wavelength band of interest is represented by the difference  $F' - F$  and is also plotted by the solid line. It is shown that a quite substantial fraction of energy is contained within the band between 2.5–42.5  $\mu\text{m}$  for the blackbody temperature range of  $-20$  to  $500 \text{ }^\circ\text{C}$ . This fraction ranges between a minimum value of about 96% at the edges to a maximum value of more than 98% around the midpoint of the temperature range between  $-20$  to  $500 \text{ }^\circ\text{C}$ . It can also be seen that for the temperature range between about  $90$ – $400 \text{ }^\circ\text{C}$  the energy fraction increases even higher from about 96% to more than 98%, something which suggests a sufficiently good accuracy of the derived results for the prescribed wavelength range.

A numerical code was developed for the calculation of the total transmittance for a fixed blackbody temperature, based on the numerical calculation of the integrals in (14) using a microcomputer. The code initially allows the calculation and storage of normalised black body spectral emissive power data files  $I_0(\lambda, 0)$  at a fixed temperature from the Planck's law. These, along with the spectral absorption data file, are employed for the calculation of total film transmittance at the specified wavelength domain, using the compounded Simpson's law. The calculation of the total transmittance values at a fixed temperature was repeatedly carried out for a radiant source temperature ranging between  $-20$  to  $500 \text{ }^\circ\text{C}$  at  $25 \text{ }^\circ\text{C}$  intervals and for a fixed film thickness.

The results were plotted in Fig. 5, in which the total transmittance is shown as a

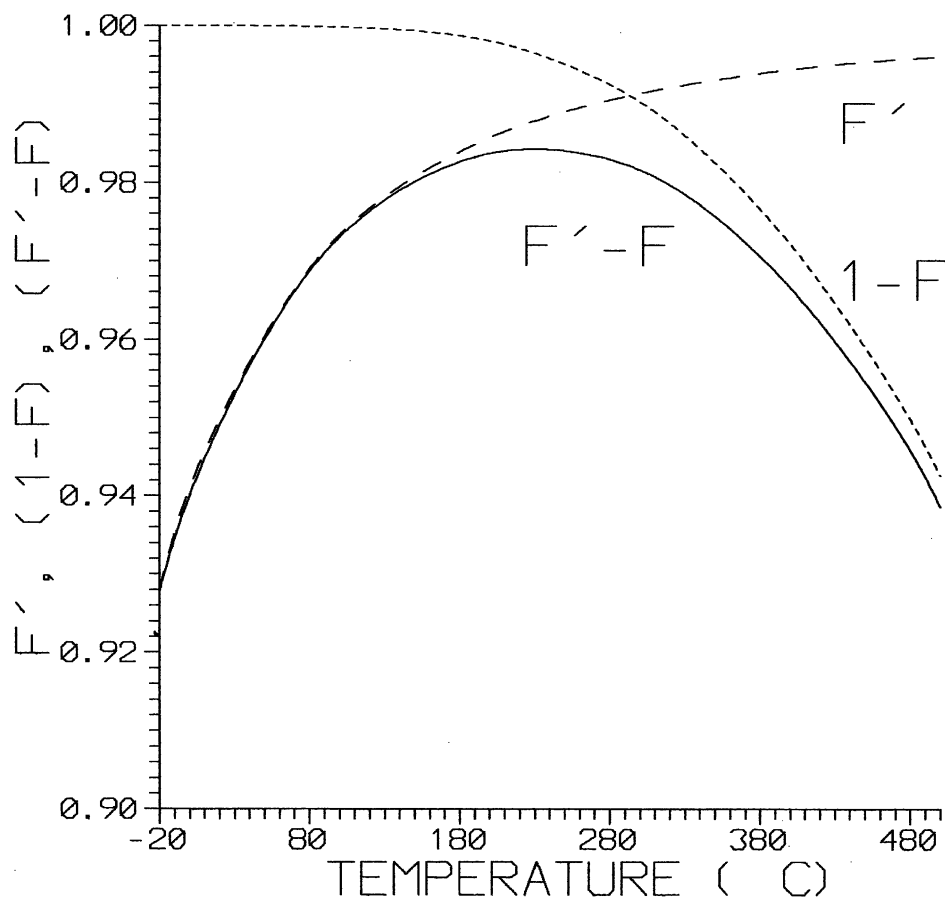


Fig. 4. Plot of the blackbody energy fractions in the wavelength bands between 0–2.5  $\mu\text{m}$  and 0–42.5  $\mu\text{m}$ ,  $F$  and  $F'$  respectively, as a function of the blackbody temperature between  $-20$  and  $500$   $^{\circ}\text{C}$ . The fractions  $1-F$  and  $F'$  are plotted with dotted and dashed lines respectively. In the same plot the total energy content of the blackbody spectrum in the wavelength range between 2.5–42.5  $\mu\text{m}$  is also plotted in solid line.

function of the radiant source temperature for four polymer film thicknesses of 0.05, 0.1, 0.2 and 0.5 mm. Clearly the derived transmittance is inversely proportional to the thickness of polymer film while the maximum transmittance varies from about 44% to almost 2% for film thicknesses ranging between 0.05 and 0.5 mm respectively. It can also be seen that for a fixed film thickness the minimum transmittance occurs at the lower radiant source temperatures which is shifted at slightly lower temperatures as the thickness increases from 0.05 to 0.5 mm. This is attributed to the fact that the bulk of blackbody energy distribution for the lower radiant source temperatures is between 9 to 12  $\mu\text{m}$  where the Tedlar film is almost completely opaque to the IR radiation. At higher temperatures the blackbody peak energy accord-

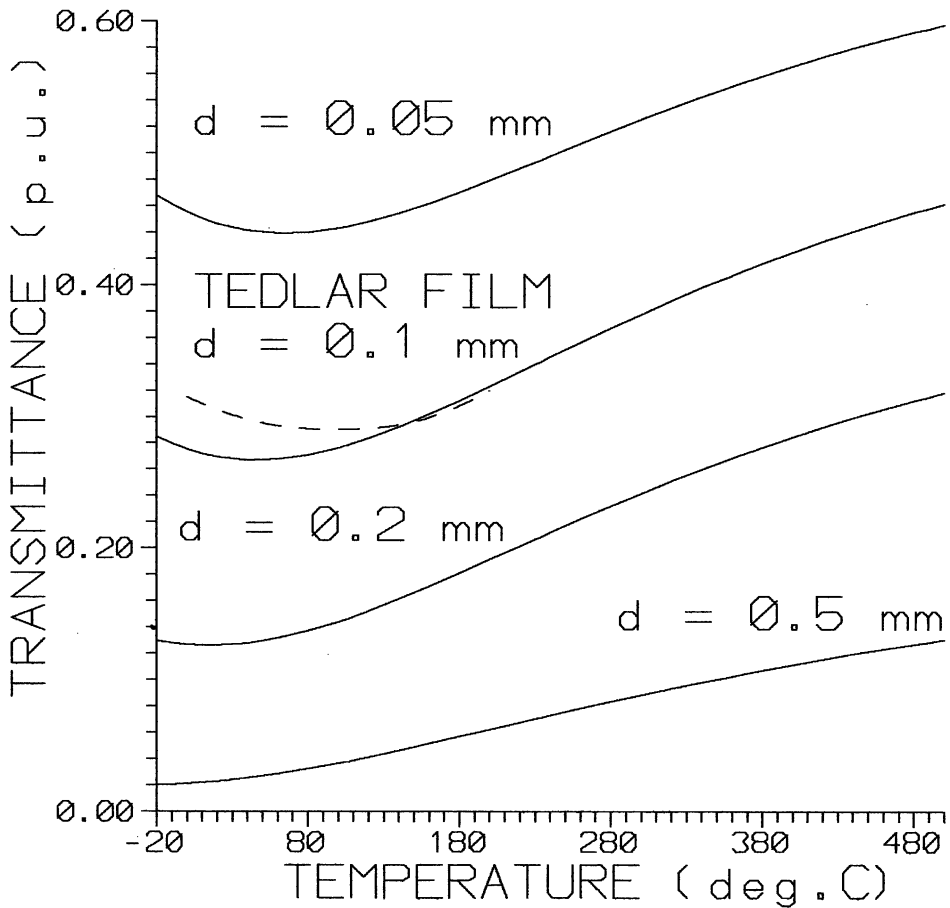


Fig. 5. The calculated total transmittance of type 400SE tedlar film was plotted against a blackbody temperature  $-20$ – $500$  °C. The four solid lines correspond to the different film thicknesses of 0.05, 0.1, 0.2 and 0.5 mm. The broken line in the same plot corresponds to the calculated transmittance of the earlier type 20, 4 mil (0.1 mm) tedlar film by Willier in the limited temperature range between  $0$ – $200$  °C.

ing to the Wien's displacement law, is shifted towards shorter wavelengths where Tedlar films are remarkably more transparent.

The calculated results from the original Willier's analysis, which correspond to the earlier type 20, 0.1 mm Tedlar film for a blackbody temperature range  $0$ – $200$  °C were transferred and plotted with a broken line in the same graph for comparison. An inspection of graphical data shows a remarkable agreement between the results from the earlier and the present analysis, especially at higher blackbody temperatures between  $100$ – $200$  °C. At the lower blackbody temperatures the agreement becomes rather poor as the blackbody temperature decreases up to around  $0$  °C, where Williers data overestimate the total transmittance by about 14%.

## 5. Conclusions

The use of Tedlar films is very promising in various fields of the contemporary technology and construction, more specifically for the design of simple low cost solar collector fields and individual collectors, as well as in horticulture, architecture and radiative cooling design. For these applications the radiative properties and more specifically the infrared transmittance of these films is necessary for a broad range of radiant source temperatures. Towards this aim an analysis was developed for the calculation of the infrared transmittance, based on existing or easily derived spectral absorption data by ordinary infrared spectrophotometric transmission measurements over an adequately wide range of wavelengths. According to the derived results, the total infrared transmittance of these films is proportional to the radiant source temperature in the temperature range between about 80–500 °C. At lower radiant source temperatures between –20 to 80 °C, it becomes only slightly dependent, irrespective of the film thickness, on the radiant source temperature, while transmittance values of about 45, 27, 13 and 2% are expected for thicknesses of 0.05, 0.1, 0.2 and 0.5 mm respectively for near ambient blackbody temperatures.

## References

- [1] Heavens OS. Optical properties of thin solid films. NY: Dover Publ. Inc, 1965.
- [2] Pankove JJ. Optical Processes in Semiconductors. NY: Dover Publ. Inc, 1971.
- [3] Hollands KGT, Wright JL. Heat loss coefficients and effective  $\tau\alpha$  products for flat-plate collectors with diathermanous covers. Solar Energy 1983;30(3):211–6.
- [4] Jannot Y, Coulibaly Y. Radiative heat transfer in a solar air heater covered with a plastic film. Solar Energy 1997;60(1):35–40.
- [5] Wijesundera NE, Iqbal M. Effect of plastic cover thickness on top loss coefficient of flat plate collectors. Solar Energy 1991;46(2):83–7.
- [6] Edwards DK, Rhee SJ. Nongray radiative and convective conductive thermal coupling in Teflon-glazed selective-black flat-plate solar collectors. Trans. of ASME Journ. of Sol. Energy Eng. 1984;106:206–11.
- [7] Catalanotti S, Cuomo V, Ruggi D. The radiative cooling of selective surfaces. Solar Energy 1975;17:83–9.
- [8] Saitoh T, Ono T. Utilisation of seasonal sky radiation energy for space cooling. Journal of Solar Energy Eng 1984;106:403–7.
- [9] Willier A. Plastic covers for solar collectors. Solar Energy 1963;7(3):148–51.
- [10] Tien CL, Chan CK, Cunningham GR. Infrared radiation of thin plastic films. Journal of Heat Transfer, Trans. of ASME: 41–45, 1972.
- [11] Rabl A, Nielsen CE. Solar ponds for space heating. solar energy 1975;17(1):1–12.
- [12] Tsilingiris PT. An accurate upper estimate for the transmission of solar radiation in salt gradient ponds. Solar Energy 1988;40(1):41–8.
- [13] Edlin E. Plastic glazings for solar energy absorption collectors. Solar Energy 1958;2(2):3–6.
- [14] Edlin FE, Willauer DE. Plastic films for solar energy applications. Proc. of the Con. New Sources of Energy Rome 1961;4:519–35.
- [15] Blaga A. Use of plastics in solar energy applications. Solar Energy 1978;21:331–8.
- [16] O'Brien-Bernini F, McGowan JG. Performance modelling of non-metallic flat plate solar collectors. Solar Energy 1984;33(3/4):305–19.
- [17] Siegel R, Howell JR. Thermal radiation heat Transfer., 3rd Ed. Hemisphere Publ. Corporation, 1992.

- [18] Lodenquai JF. Determination of absorption coefficients of thin films. *Solar Energy* 1994;53/2(2):209–10.
- [19] Edlin F. Optical properties of materials used in solar energy systems. In: Kreider JF, Kreith F, editors. *Solar Energy Handbook*. New York: McGraw-Hill; 1981.
- [20] DuPont. Technical Information 400SE PVF Film Rev. 7–82, 1982.