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This is an Accepted Manuscript of an article published by Taylor & Francis in HVAC&R Research on October 1, 2011, available online: <http://www.tandfonline.com/doi/abs/10.1080/10789669.2011.591257>

A METHOD FOR DETERMINING THE EFFECTIVE LONGWAVE RADIATIVE PROPERTIES OF PLEATED DRAPERIES

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ABSTRACT

Draperies, attached to fenestration, offer a cost effective strategy in controlling solar gain since draperies have the potential to reduce building peak load and annual energy consumption. The performance of a drapery is dependent on its solar optical and longwave radiative properties. The current study considers the determination of spatially averaged (effective) longwave radiative properties of draperies. As a first step, the longwave properties of fabrics were obtained by taking measurements with an infrared reflectometer using two backing surfaces. The measurement results enabled simple equations to be developed relating emittance and longwave transmittance to openness, emittance and longwave transmittance of the fabric structure. In turn, the effective longwave properties of a pleated drapery are modeled using a net radiation scheme with fabric longwave properties as input. The model approximates a drapery as a series of uniformly arranged rectangular pleats. The effective longwave properties of the pleated drapery are calculated by considering an enclosure which is representative of the entire series of pleats. The longwave properties of the drapery are functions of only pleat geometry and openness of the fabric. The model compares favourably with expected trends and limits. The effect of pleating (folding ratio) is also examined.

INTRODUCTION

Draperies may offer a cost effective strategy in reducing solar heat gain through windows. As such, the ability to accurately quantify the reduction in cooling load that draperies deliver would be an asset to HVAC engineers in particular and building designers in general.

The energy performance of windows with draperies can be modeled using a two-step procedure. In the first step, solar radiation is considered. This requires the determination of solar optical properties of each layer in the glazing/drapery system. A drapery layer can be characterized by making the assumption that the non-homogeneous layer can be represented by an equivalent homogenous layer that is assigned spatially-averaged (effective) optical properties. This approach has been used in a number of studies to characterize venetian blinds (e.g., Parmelee and Aubele 1952, Rheault and Bilgen 1989, Pfrommer et al. 1996, Rosenfeld et al. 2000, Yahoda and Wright 2004, 2005) and has been shown to provide accurate results (e.g., Kotey et al. 2009).

Careful consideration of solar radiation incident on a drapery layer with some openness reveals that a portion of the incident radiation passes undisturbed through the openings and the remaining portion is intercepted by the yarn. The portion of the intercepted radiation that is not absorbed will be scattered and will leave the layer as an apparent reflection or transmission. These scattered components are assumed to be uniformly diffuse. In addition, a drapery layer will generally transmit longwave radiation (i.e., it is diathermanous), by virtue of its openness, and effective longwave properties are assigned accordingly. The effective solar optical properties can be used as part of a multilayer calculation that considers beam and diffuse components of solar radiation as they interact with a multilayer assembly (e.g., Wright and Kotey 2006). This calculation estimates the system solar transmission and absorbed solar

components. The absorbed solar components appear as energy source terms in the second step – the heat transfer analysis.

The heat transfer analysis involves the formulation of energy balance equations and requires both longwave properties and convective heat transfer coefficients as input. The simultaneous solution of the energy balance equations yields the temperature as well as the convective and radiative fluxes. The current study considers the determination of the effective longwave properties of pleated draperies. This is achieved by a two-step procedure described below.

In the first step, spectral measurements of normal-hemispherical longwave reflectance and transmittance were obtained for fabrics using a commercially available infrared reflectometer (Surface Optics Corporation 2002). The spectral data showed that fabrics are generally not spectrally selective. Since the aim of the current study is to generate total (spectral-averaged) properties for building energy simulation, no spectral data are presented. The total longwave properties, including emittance, were calculated with respect to blackbody spectrum at a given temperature (ASTM E408-71 1971). The procedure entailed the solution of two simultaneous equations resulting from the reflectance measurements with the fabric sample backed by two surfaces with different reflectance values. A similar procedure was used by Christie and Hunter (1984) to determine the longwave properties of thin diathermanous films using DB-100 infrared reflectometer. Having obtained emittance and longwave transmittance of the fabrics, it was recognised that these quantities are simple functions of openness, emittance and longwave transmittance of the fabric structure. Furthermore, the emittance and the longwave transmittance of the fabric structure were found to be constant regardless of the colour of the fabric.

In the second step, a drapery layer was modeled as a series of uniformly arranged rectangular pleats. The effective longwave properties of the drapery layer were calculated by considering an enclosure which is representative of the entire series of pleats. The calculation involved a conventional grey enclosure net-radiation analysis with shape factors to track radiant exchange between surfaces. Given the surface longwave properties from the first step, the effective longwave properties of the representative enclosure were readily obtained.

TEST SAMPLES

A variety of drapery fabrics were obtained with the primary aim of locating samples that fit into each of the nine designations described by Keyes (1967). In that work, fabrics were classified as being open (I), semi-open (II), or closed (III) weave, and as light (L), medium (M), or dark (D) coloured. With the exception of designation IIID (closed weave dark) which could not be located, all designations were obtained. Also included in the sample set was a sheer fabric which did not fall into any of the customary designations. The dimensions of each sample were 5 cm by 5 cm (2 in by 2 in) and the thicknesses of the samples ranged from 0.1 mm (0.004 in) to 1.0 mm (0.04 in). Figure 1 shows the samples considered; and the type, colour and openness, A_o , of each fabric sample are summarized in Table 1. Since A_o is equivalent to the solar beam-beam transmittance at normal incidence ($\tau_{sol,bb}^m(\theta = 0)$), the values of A_o were obtained from spectrophotometer measurements (e.g., Kotey et al. 2009a, 2009b and 2009c).

EXPERIMENTAL PROCEDURE

Infrared Reflectometer

A commercially available FTIR (Fourier Transform Infrared Spectroscopy) reflectometer, SOC 400T, was used in this study. It is a portable, self-calibrating instrument with a reflectance repeatability of $\pm 1\%$ and a spectral resolution selectable from 4 to 32 cm^{-1} (1.6 to 12.6 in^{-1}). The reflectometer is designed to measure normal-hemispherical reflectance of an opaque surface in the wavelength range of $2.0 < \lambda < 25.0 \text{ }\mu\text{m}$ (infrared region). The instrument collects many infrared spectra over a short period of time.

The infrared spectra are automatically averaged and integrated with respect to the black body spectrum at selectable temperature range. Emittance values are evaluated from the integrated values of the spectral reflectance. Detailed description and the operating principles of the SOC 400T is documented by Surface Optics Corporation (2002) and Jaworske and Skowronski (2000).

The SOC 400T is the current state-of-the-art instrument that may be offered as a substitute for the well-known Gier Dunkle DB-100 infrared reflectometer. This is because the SOC 400T has the capability to measure reflectance over a large spectral range and subsequently evaluates emittance over a large temperature range. The Gier Dunkle DB-100, on the other hand, measures total reflectance in the vicinity of $9.7 \text{ }\mu\text{m}$ while emittance can only be evaluated at room temperature. Another remarkable difference between the two instruments is that the DB-100 measures hemispherical-normal reflectance whereas the SOC 400T measures normal-hemispherical reflectance.

Measurements

As stated at the onset, the SOC 400T is designed to measure infrared reflectance of samples that are opaque to infrared radiation. However, by following a general theory and measurement procedure documented by Christie and Hunter (1984), the reflectometer can be adapted to measure both infrared reflectance and transmittance of diathermanous samples. Emittance is easily estimated from the reflectance and the transmittance measurements.

The SOC 400T was calibrated by first leaving the measurement port uncovered while the room was scanned and the zero spectrum recorded. Care was taken not to obstruct the field of view of the measurement port. A specular gold disk was then placed over the measurement port and the reference spectrum recorded. The gold disk has a constant reflectance value of 0.98 in the wavelength range of $2.0 < \lambda < 25.0 \mu\text{m}$. To confirm this reflectance value, a reflectance measurement was obtained after calibration while the gold disk was still in place. This confirmation was necessary since the gold disk also served as a backing surface. As such, its reflectance value needed to be known accurately. The reflectance of a second backing surface (black surface) was also measured and found to be 0.07.

Having obtained the calibration spectra and the reflectance values of the two backing surfaces, two sets of spectral reflectance measurements were taken for each sample listed in Table 1. The first set of measurements was obtained by placing the sample over the measurement port with the gold surface backing it. The second set of measurements was obtained by replacing the gold surface with the black surface. In both cases, the total emittance of the opaque surface formed by the sample and the backing surface were computed from the spectral reflectance measurements at temperatures ranging from 290 to 300 K (62.3 to 80.3 °F).

LONGWAVE PROPERTIES OF FABRICS

Consider longwave radiation incident on the surface of a given fabric sample. Assuming the sample is grey, the longwave reflectance, ρ_{lw}^m , the longwave transmittance, τ_{lw}^m and the emittance, ϵ^m , are related by principle of energy conservation and Kirchoff's law,

$$\rho_{lw}^m = 1 - \tau_{lw}^m - \epsilon^m \quad (1)$$

The superscript “m” is used to designate a fabric (i.e., material) property as opposed to the corresponding effective longwave property of the pleated drapery. For an opaque sample, $\tau_{lw}^m = 0$ and

$$\rho_{lw}^m = 1 - \epsilon^m \quad (2)$$

The SOC 400T measures the spectral reflectance of an opaque surface, integrates the spectral data with respect to black body spectrum at a given temperature and computes ϵ^m . The value of ρ_{lw}^m can subsequently be calculated from Equation 2.

To estimate ϵ^m and τ_{lw}^m of a diathermanous sample, we resort to the procedure outlined by Christie and Hunter (1984). Christie and Hunter used theory to derive reflectance equations by considering longwave radiation incident on a thin diathermanous film backed by two different surfaces. The system (i.e., the diathermanous film together with the backing surface) reflectance in each case is dependent on the film and the backing surface reflectance

values as well as the film transmittance. Given the reflectance values of the backing surfaces,

the film reflectance, ρ_{lw}^m and the film transmittance, τ_{lw}^m were obtained as

$$\rho_{lw}^m = \frac{(\rho_{B1}/\rho_{B2})\rho_{S2} - \rho_{S1}}{(\rho_{B1}/\rho_{B2}) + \rho_{B1}(\rho_{S2} - \rho_{S1}) - 1} \quad (3)$$

and

$$\tau_{lw}^m = \sqrt{\frac{(\rho_{S1} - \rho_{lw}^m)(1 - \rho_{lw}^m \rho_{B1})}{\rho_{B1}}} \quad (4)$$

where ρ_{S1} and ρ_{S2} are the system reflectance values with backing surfaces 1 and 2 in place

while ρ_{B1} and ρ_{B2} are the reflectance values of backing surfaces 1 and 2. Having obtained

ρ_{lw}^m and τ_{lw}^m , ϵ^m can be calculation from Equation 5:

$$\epsilon^m = 1 - \tau_{lw}^m - \rho_{lw}^m \quad (5)$$

Typical uncertainties associated with the values ρ_{lw}^m , τ_{lw}^m and ϵ^m were estimated to be ± 0.016 , ± 0.024 , and ± 0.028 , respectively. Details of the uncertainty analysis are discussed in Kotey (2009).

Relationship between Fabric Longwave Properties and Openness

To establish a relationship between ϵ^m and A_o , measured values of ϵ^m were plotted against $1 - A_o$ as shown in Figure 2a. Note that values of A_o were obtained from solar

optical measurements (Kotey et al. 2009a). Equation 6 is the result of a regression fit (goodness of fit, R-squared = 0.94) obtained from the measured data.

$$\varepsilon^m = 0.87(1 - A_o) \quad (6)$$

The straight line shown in Figure 2a represents Equation 6. Clearly, there is a strong correlation between ε^m and $1 - A_o$. The regression fit was set to pass through the origin since in the limit where $A_o \rightarrow 1$ (i.e., the fabric disappears) $\varepsilon^m \rightarrow 0$ and Equation 6 correctly satisfies this limiting case.

A similar relationship was established between τ_{lw}^m and A_o by plotting values of $1 - \tau_{lw}^m$ against $1 - A_o$. See Figure 2b. Equation 7 is the result of a regression fit (goodness of fit, R-squared = 0.95) obtained from the plot.

$$1 - \tau_{lw}^m = 0.95(1 - A_o) \quad (7)$$

Again, there exists a strong correlation between τ_{lw}^m and A_o as seen in Figure 2b. The straight line shown in Figure 2b, representing Equation 7, passes through the origin since in the limit where $A_o \rightarrow 1$, $\tau_{lw}^m \rightarrow 1$. Substituting $1 - A_o$ from Equation 7 into Equation 6 gives relationship between ε^m and τ_{lw}^m , i.e.,

$$\varepsilon^m = 0.92(1 - \tau_{lw}^m) \quad (8)$$

To confirm this relationship, measured values of ϵ^m were plotted against $1 - \tau_{lw}^m$ as shown in Figure 2c. A regression fit (goodness of fit, R-squared = 0.99) given by Equation 8 was indeed realised. Such a strong correlation further validates the relationships established between longwave properties and openness.

EFFECTIVE LONGWAVE PROPERTIES OF PLEATED DRAPERIES

A drapery consists of a series of fabric pleats that are non-uniform. Similar to the approach used by Farber et al. (1963) in determining the effective solar properties, rectangular pleats have been used as an approximation to determine the effective longwave properties. Since the pleats are repetitive, an enclosure formed by two consecutive pleats will represent an entire drapery layer. A cross-section of such an enclosure is shown in Figure 3a. The representative enclosure is made up of two sub-enclosures with pleat width, w , and pleat spacing, s . Fictitious surfaces at the front and back openings complete the enclosure.

The longwave properties of the drapery are influenced by pleat geometry, which can be described in terms of folding ratio, Fr , or percent fullness. The folding ratio is defined as the total length of the fabric divided by the length of the drapery, L . When the length of the fabric is twice that of the drapery, $Fr = 2$, the drapery is described as having 100% fullness. Figure 3 shows draperies with different values of Fr and percent fullness. The geometry of Figure 3 gives $Fr = 1 + w / s$.

Consider longwave radiation, I_{lw} , incident on a representative enclosure. See Figure 4. Pleated drapery longwave radiative properties are modeled based on conventional grey enclosure with the following assumptions:

- The thickness of the fabric is negligible

- Fabric surfaces are isothermal
- Fabric longwave properties are independent of temperature
- Fabric surfaces are perfectly flat
- Incident longwave radiation is uniformly distributed
- Fabric surfaces are uniformly irradiated

Since longwave radiation is originally diffuse, it remains diffuse within the enclosure as it interacts with the surfaces before finally emerging in the forward (transmission) and backward (reflection) direction. The effective longwave transmittance, τ_{lw}^{eff} and the effective longwave reflectance, ρ_{lw}^{eff} of the drapery are determined accordingly. Note that front effective longwave properties of pleated drapery are equal to the corresponding back effective longwave properties since fabric longwave properties are free from front/back influence. The radiant analysis can be performed with the following definitions in mind:

J_i = radiosity of surface i

G_i = irradiance at surface i

The following equations are applied:

$$J_1 = \rho_{lw}^m G_1 + \tau_{lw}^m I_{lw} \quad (9)$$

$$J_2 = \rho_{lw}^m G_2 + \tau_{lw}^m G_8 \quad (10)$$

$$J_4 = \rho_{lw}^m G_4 + \tau_{lw}^m G_6 \quad (11)$$

$$J_6 = \rho_{lw}^m G_6 + \tau_{lw}^m G_4 \quad (12)$$

$$J_7 = \rho_{lw}^m G_7 \quad (13)$$

$$J_8 = \rho_{lw}^m G_8 + \tau_{lw}^m G_2 \quad (14)$$

The radiosity of surface 5 is $J_5 = I_{lw}$, while the radiosity of surface 3 is $J_3 = 0$.

The diffuse irradiance on each surface of the top or bottom sub-enclosure is given by

$$G_i = \sum_j F_{ij} J_j \quad (15)$$

The view factor, F_{ij} , is the fraction of diffuse radiation leaving surface i that is intercepted by surface j . The values of F_{ij} can be determined by Hottel's crossed string rule (e.g., Hollands 2004). Since all surfaces are flat, $F_{ii} = 0$. The irradiance on each surface of either sub-enclosure can be calculated using Equation 15, with the subscripts i and j applied to the given number of surfaces in that sub-enclosure. For example, the irradiance on surface 4 of the top sub-enclosure is

$$G_4 = F_{44} J_4 + F_{41} J_1 + F_{42} J_2 + F_{43} J_3 \quad (16)$$

Equations 9 to 14 are linear and can be solved by matrix reduction with I_{lw} set to unity.

The values of τ_{lw}^{eff} and ρ_{lw}^{eff} are as follows:

$$\tau_{lw}^{\text{eff}} = \frac{G_3 + \tau_{lw}^m G_7}{2} \quad (17)$$

$$\rho_{lw}^{\text{eff}} = \frac{\rho_{lw}^m + \tau_{lw}^m G_1 + G_5}{2} \quad (18)$$

From the principle of energy conservation and Kirchhoff's law, the effective emittance of the pleated drapery, ε^{eff} , can be calculated from Equation 18.

$$\varepsilon^{\text{eff}} = 1 - \tau_{\text{lw}}^{\text{eff}} - \rho_{\text{lw}}^{\text{eff}} \quad (19)$$

DISCUSSION

Longwave Properties of Fabrics

Examining Equations 6 and 7, it can be seen that the longwave properties of fabrics are only dependent on the openness. Since the openness of fabrics is free of front/back influence, it implies that front longwave properties are equal to the corresponding back longwave properties.

The coefficient in Equation 6 may be considered to be the total hemispherical emittance of the fabric structure. This is because when $A_o = 0$, the emittance of the fabric is simply equal to the emittance of the structure. The measurements show that irrespective of the colour of the fabric, the emittance of the structure may be considered to be constant.

Table 2 summarises the estimated total hemispherical emittance, transmittance and reflectance of the structure of the fabrics. Also shown in Table 2 are the total normal emittance values of typical opaque surfaces at specified temperatures (Modest 1993, Siegel and Howell 1993, Incropera and DeWitt 2001). For smooth surfaces, the hemispherical emittance can be estimated from the normal emittance values. Materials with high emittance tend to behave like dielectrics and therefore have a hemispherical emittance that is 3 to 5% greater than the normal emittance (Modest 1993, Hollands 2004). Note that the

aforementioned conversion factors were not applied since fabrics generally have rough surfaces and the normal to hemispherical emittance conversion is not applicable. From the literature survey, it can be seen that a typical fabric made from dyed cloth has a high emittance which is independent of the colour of the dye (paint).

Consideration will now turn to the behaviour of longwave transmittance of the fabrics when $A_o = 0$. From Equation 7, it is evident that τ_{lw}^m does not necessarily drop to zero under such circumstances. Substituting $A_o = 0$ into Equation 7 give τ_{lw}^m of the fabric structure which is included in Table 2. The finite value of τ_{lw}^m when $A_o = 0$ may be attributed to multiple reflections between yarns of the fabric and subsequent transmission through the interstices of the fabric structure. To further substantiate this argument, the ρ_{lw}^m value of the fabric structure was estimated from Equation 1 given the values of τ_{lw}^m and ϵ^m . The result is also included in Table 2. It is clearly seen from Table 2 that fabrics generally have low values of ρ_{lw}^m and correspondingly low values of τ_{lw}^m as expected.

Effective Longwave Properties of Pleated Draperies

Typical draperies with sheer fabric ($A_o = 0.44$), open weave fabric ($A_o = 0.34$), semi-open weave fabric ($A_o = 0.15$) and closed weave fabric ($A_o = 0.01$) were selected. The effective longwave properties of draperies made from the selected fabrics were calculated using models developed in the preceding sections. The results are shown in Figure 5 for the variation of effective longwave properties with Folding ratio, Fr. Note that for $w = 0$ (Fr = 1),

the drapery is flat and the effective longwave properties of the drapery correspond to the longwave properties of the fabric.

It can be seen that ϵ^{eff} for draperies always increases with increasing Fr regardless of fabric openness. Draperies with sheer fabric show the sharpest increase in ϵ^{eff} with Fr while draperies with closed weave fabric show the least increase in ϵ^{eff} with Fr. In other words, the greater the value of the openness, the sharper the increase in ϵ^{eff} with Fr. On the other hand, τ_{1w}^{eff} for the draperies considered always decreases with Fr. It is to be expected that pleating will consistently decrease τ_{1w}^{eff} because there is more opportunity for radiation to be absorbed in the fabric because of the inter-reflection that arises if the fabric can view itself.

The calculated ρ_{1w}^{eff} reveal an interesting phenomenon. Draperies with sheer and open weave fabrics have ρ_{1w}^{eff} increasing to a maximum at Fr = 2, and then decreasing gradually as Fr increases. On the contrary, draperies with semi-open weave and closed weave fabrics have ρ_{1w}^{eff} always decreasing gradually as Fr increases. Again, this is due to self-viewing. Some of the radiation that passes through the front surface of the drapery (fabric surface cd) will encounter one of the perpendicular surfaces (dg or ac) where a portion will transmit to the adjacent cavity and a portion of this radiation will exit through the opening (fictitious surface cd), either directly or by intermediate reflection. This effect is most prevalent in fabrics with higher values of openness.

CONCLUSIONS

A method for determining the longwave radiative properties of pleated draperies is presented. First, a portable infrared reflectometer in conjunction with two backing surfaces was used to measure the longwave radiative properties of fabrics. It was found that the emittance and longwave transmittance of fabrics are simple functions of openness as well as the emittance and longwave transmittance of the fabric structure. Second, a model that approximates a drapery layer as a series of uniform rectangular pleats is developed. The model was used to calculate the effective longwave radiative properties of pleated draperies with fabric properties as input. The model is based on conventional grey enclosure analysis with fabric surfaces assumed to be perfectly flat, isothermal, uniformly irradiated, emit/transmit/reflect diffusely in the longwave spectrum. The effective longwave radiative properties of a pleated drapery were determined by introducing an external uniformly diffuse longwave radiation on an enclosure that represents an entire drapery layer. The results showed that the effective longwave radiative properties of a pleated drapery are only dependent on the openness of the fabric and the folding ratio of the pleated drapery. The results also offer significant value in modeling pleated draperies in the context of building energy simulation.

Acknowledgments

Financial support in terms of a Natural Sciences and Engineering Research Council (NSERC)

Postdoctoral Fellowship to N.A. Kotey is gratefully acknowledged.

Nomenclature

A_o	openness
ε	emittance
ρ	reflectance
τ	transmittance
θ	angle of incidence
λ	wavelength
G	irradiance
F_{ij}	view factor from surface i to surface j
J	radiosity
w	pleat width
s	pleat spacing
I	incident radiation

Subscripts

bb	beam-to-beam solar optical property
$B1$	backing surface 1
$B2$	backing surface 2
lw	longwave
sol	shortwave (solar)
$S1$	system 1 (diathermanous layer with backing surface 1)
$S2$	system 1 (diathermanous layer with backing surface 2)

Superscripts

m	fabric material
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Table 1: Description of Fabric Samples

Type	Colour	Openness
Sheer	Cream	0.44
Open weave, light coloured (IL)	White	0.24
Semi-open weave, light coloured (IIL)	White	0.01
Closed weave, light coloured (IIIL)	White	0.01
Open weave, medium coloured (IM)	Brown	0.34
Semi-open weave, medium coloured (IIM)	Green	0.02
Closed weave, medium coloured (IIIM)	Blue	0.01
Open weave, dark coloured (ID)	Black	0.20
Semi-open weave, dark coloured (IID)	Black	0.05

Table 2: Summary of Longwave Properties

Shading Material	Experimental Results			Results from Literature Survey		
	Estimated hemispherical emittance of structure at 300 K	Estimated hemispherical transmittance of structure	Estimated hemispherical reflectance of structure	Opaque surfaces	Surface temp (K)	Typical total normal emittance
Fabrics	0.87	0.05	0.08	Paint (all colours)	300	0.92-0.98
				Cloth	293	0.77-0.78

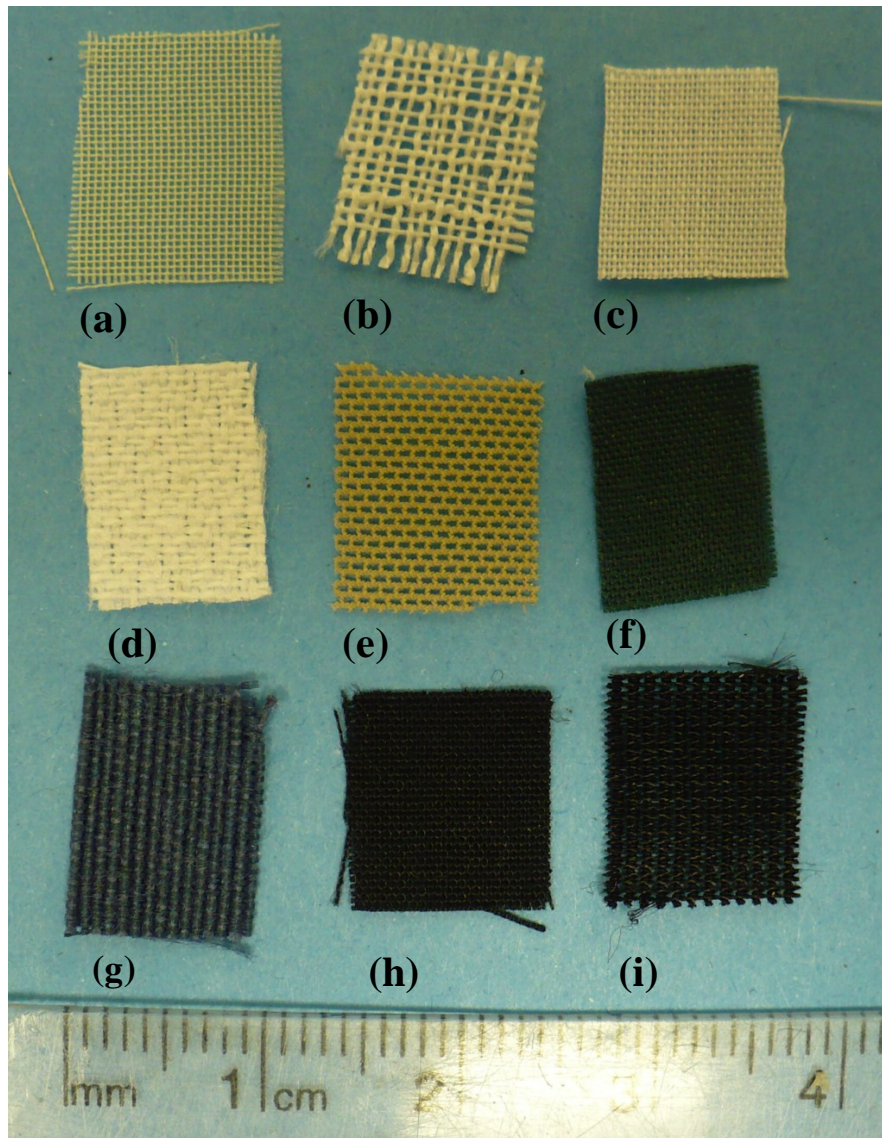


Figure 1: Photograph of Fabric Samples (a) Sheer (b) IL (c) IIL (d) IIIL (e) IM (f) IIM (g) IIIM (h) ID (i) IID

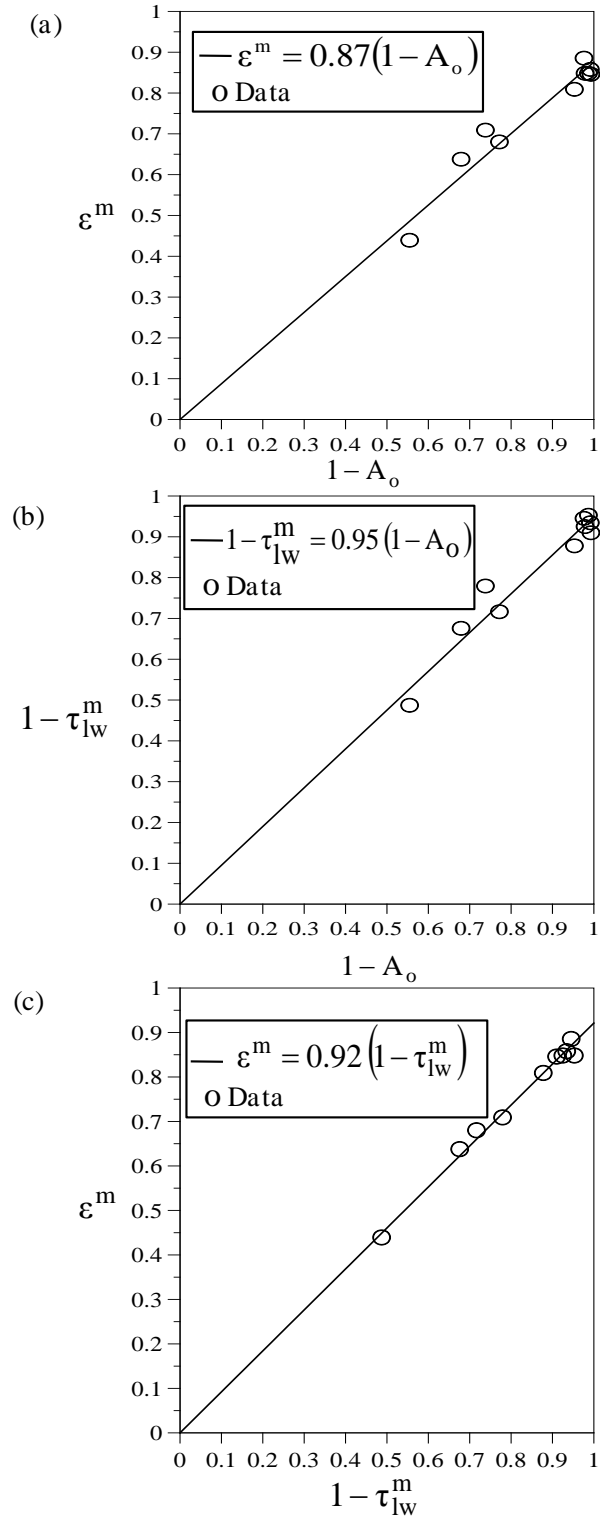


Figure 2: Longwave Radiative Properties of Fabrics (a) ϵ^m versus $1 - A_o$

(b) $1 - \tau_{lw}^m$ versus $1 - A_o$ (c) ϵ^m versus $1 - \tau_{lw}^m$

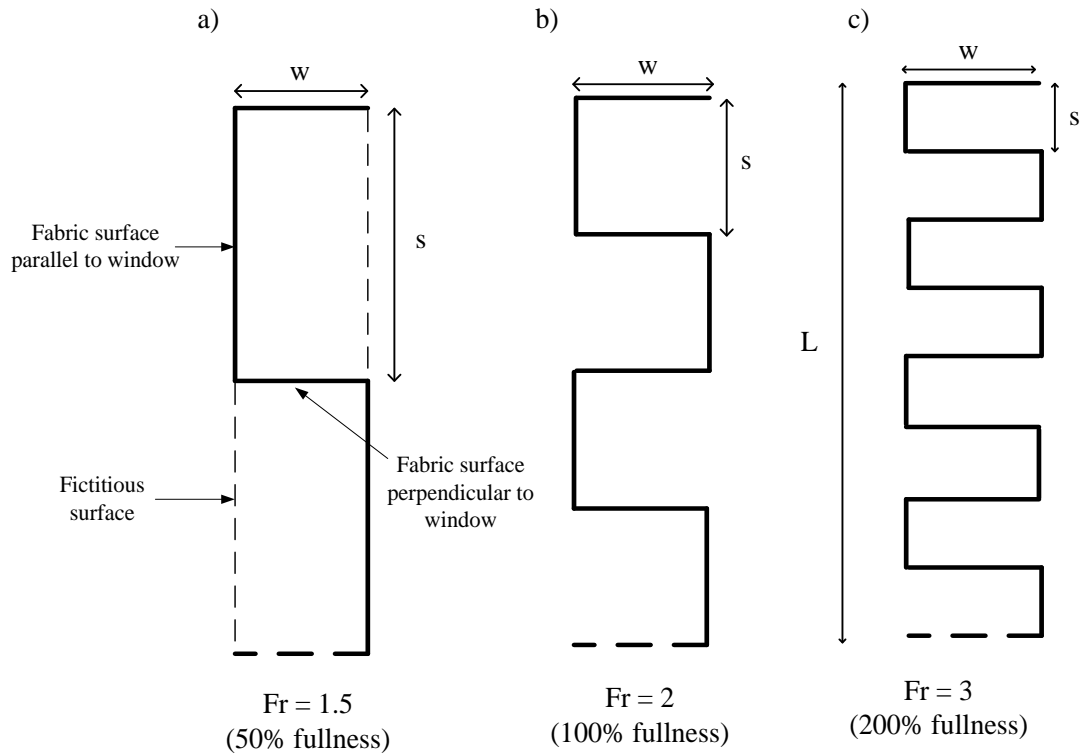


Figure 3: Cross-Section of Drapery Pleats with Different Values of Folding Ratio and Percent Fullness.

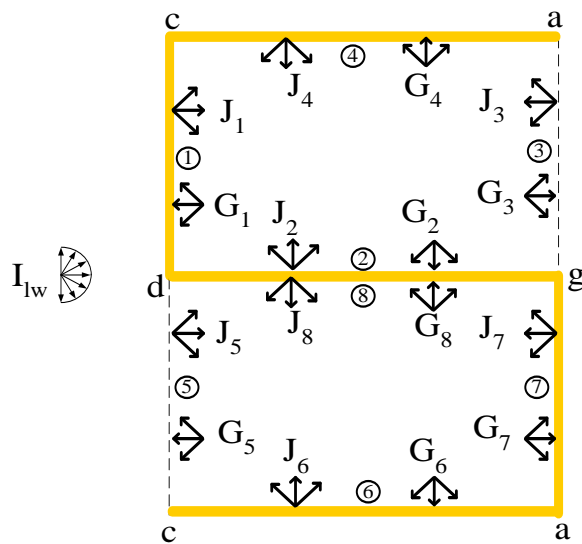


Figure 4: Calculating Effective Longwave Radiative Properties of Pleated Drapery

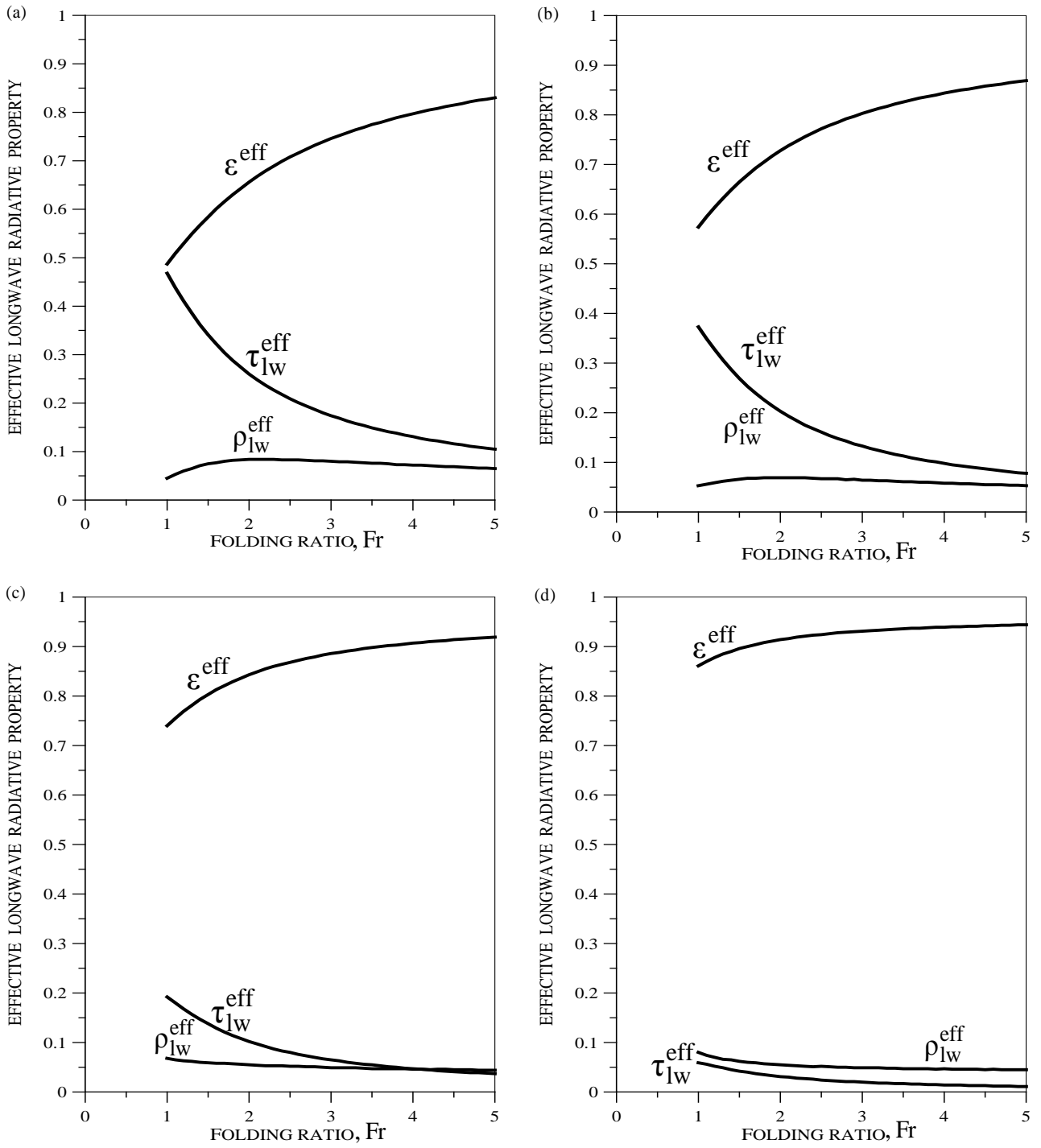


Figure 5: Effective Longwave Properties of Pleated Draperies Versus Folding Ratio, Fr: (a) Sheer ($A_o = 0.44$), (b) Open Weave ($A_o = 0.34$), (c) Semi-Open Weave ($A_o = 0.15$), (d) Closed Weave ($A_o = 0.01$).