PAULO OTTO BEYER
Eng. Mecânico, Prof., Dr.
Ventilação, Aquecimento, Refrigeração e Ar Condicionado

Porto Alegre, 12 de junho de 2008

Ao Ecotelhado
A/C Eng. João Manuel
ecotelhado@ecotelhado.com.br

Ref.: Condutividade Térmica Equivalente do Ecotelhado

Prezados Senhores

Apresentamos resultados da determinação da condutividade térmica equivalente do Ecotelhado.

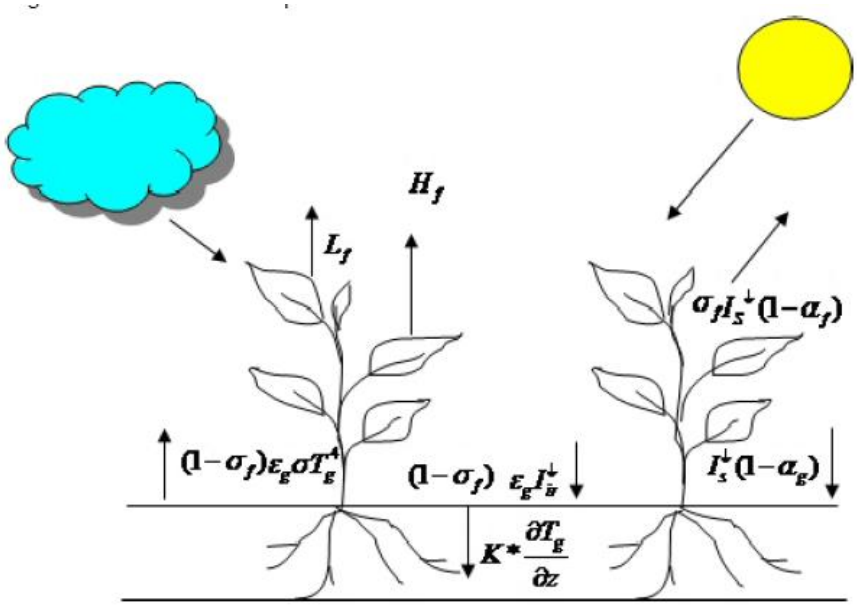
1 Metodologia

A determinação foi feita por simulação computacional usando o EnergyPlus, programa oficial de simulação termo-energética de edificações do Departamento de Energia dos EUA.

Para tanto foram simuladas três coberturas, todas constituídas basicamente por telhas de fibrocimento, sendo que uma delas não recebeu nenhum material adicional, uma delas foi recoberta com o Ecotelhado e outra foi recoberta com poliuretano com propriedades definidas.

As simulações foram realizadas procurando definir uma espessura do poliuretano que resultasse no desempenho termo-energético mais próximo do apresentado pelo Ecotelhado.

As simulações foram realizadas durante o verão em São Paulo, utilizando o modelo de Ecoroof do EnergyPlus. Abaixo pode ser visto um desenho com o modelamento do Ecoroof pelo EnergyPlus.



No modelamento foram levados em conta os seguintes parâmetros básicos:

- Absorção da radiação solar pelas folhas

Rua Gen. Gomes Carneiro, 188 – Fone: 0xx51-32174724, Cel. 93311541
CREA 27364-D - paulo@beyer.eng.br - www.beyer.eng.br - P.Alegre - RS

- Absorção da chuva pelo solo
- Troca de calor sensível entre as folhas e o ar
- Fluxo de calor latente entre as folhas e o ar
- Emissão de radiação pelas folhas
- Absorção e emissão de radiação pelo solo
- Condução de calor pelo solo

Os dados informados basearam-se em uma amostra do Ecotelhado a nós fornecida pela Ecotelhado, com a finalidade de determinação e medição dos parâmetros básicos. A seguir podem ser vistas duas fotos da amostra usada como base:

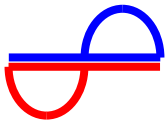
2 Dados de Entrada

A seguir podem ser vistos os principais dados informados ao programa de simulação Energy-Plus:

```
RunPeriod,
   12,                !- Begin Month
   21,                !- Begin Day Of Month
   3,                 !- End Month
   21,                !- End Day Of Month

Location,
   SAO_PAULO_BRA Design_Conditions,  !- LocationName
   -23.62,            !- Latitude {deg}
   -46.65,            !- Longitude {deg}
   -3.00,             !- TimeZone {hr}
   803.00;            !- Elevation {m}

SITE PRECIPITATION,
   SCHEDULED DESIGN,       !- Type of Description
   1,                      !- Design Annual Precipitation
   PrecipitationAtlanta,   !- Schedule Name for Precipitation Rates
   1;                      !- Nominal Annual Precipitation

ROOF IRRIGATION,
   SMART SCHEDULE,         !- Type of Description
   IRRIGATIONSCHD;         !- Schedule Name for Irrigation Rates

MATERIAL:REGULAR,
   BLBD - ASBESTOS CEMENT 1 / 4 IN,  !- Name
   MediumRough,       !- Roughness
   6.3999998E-03,     !- Thickness {m}
   0.5700000,         !- Conductivity {W/m-K}
   1922.210,          !- Density {kg/m3}
   830.0000,          !- Specific Heat {J/kg-K}
   0.9000000,         !- Absorptance:Thermal
   0.7500000,         !- Absorptance:Solar
   0.7500000;         !- Absorptance:Visible

MATERIAL:ECOROOF, (Ver anexo para definições)
   BaseEco,           !- Name
   0.1,               !- Height of Plants {m}
   10,                !- Leaf Area Index {dimensionless}
   0.2,               !- Leaf Reflectivity {dimensionless}
   0.95,              !- Leaf Emissivity
   175,               !- Minimum Stomatal Resistance (s/m)
   EcoRoofSoil,       !- Name Of the Soil Layer
   MediumSmooth,      !- Roughness
   0.075,             !- Thickness {m}
   0.044,             !- Conductivity (dry soil) {W/m-K}
   100,               !- Density (dry soil) {kg/m3}
   1230,              !- Specific Heat (dry soil) {J/kg-K}
```

```
   0.95,                !- Absorptance:Thermal
   0.7,                 !- Absorptance:Solar
   0.7,                 !- Absorptance:Visible
   0.5,                 !- Max volumetric moisture content of the soil layer (saturation)
   0.01,                !- Min (residual) volumetric moisture content of the soil layer
   0.2;                 !- Initial volumetric moisture content of the soil layer

MATERIAL:REGULAR,
   INS - EXPANDED POLYURETHANE R11 2 IN,  !- Name
   VeryRough,       !- Roughness
   0.05,            !- Thickness {m}
   0.025,           !- Conductivity {W/m-K}
   24,              !- Density {kg/m3}
   1590,            !- Specific Heat {J/kg-K}
   0.9000000,       !- Absorptance:Thermal
   0.5000000,       !- Absorptance:Solar
   0.5000000;       !- Absorptance:Visible

CONSTRUCTION,
   telha,                                 !- Name
   BLBD - ASBESTOS CEMENT 1 / 4 IN;  !- Outside Layer

CONSTRUCTION,
   cobertura verde,                       !- Name
   BaseEco,                               !- Outside Layer
   BLBD - ASBESTOS CEMENT 1 / 4 IN;  !- Layer #2

CONSTRUCTION,
   cobertura isolada,                              !- Name
   INS - EXPANDED POLYURETHANE R11 2 IN,  !- Outside Layer
   BLBD - ASBESTOS CEMENT 1 / 4 IN;               !- Layer #2

Surface:HeatTransfer,
   ZN10_Core_Space_2:Roof,                !- User Supplied Surface Name
   roof,                                  !- Surface Type
   telha ou cobertura verde ou cobertura isolada,  !- Construction Name of the Surface
   ZN10_Core_Space_2,                     !- Zone Name
   ExteriorEnvironment,                   !- OutsideFaceEnvironment
   ,                                      !- OutsideFaceEnvironment Object
   SunExposed,                            !- Sun Exposure
   WindExposed,                           !- Wind Exposure
   0.000,                                 !- View Factor to Ground
   4,                                     !- Number of Surface Vertex Groups -- Num-
ber of (X,Y,Z) groups in this surface
   15.860,          !- Largura {m}
   15.860,          !- Comprimento {m}

SCHEDULE:COMPACT,
   IRRIGATIONSCHD,        !- Name
   Any Number,            !- ScheduleType
```

```
   Through: 3/31,              !- Complex Field #1
   For: Alldays,               !- Complex Field #2
   Until: 07:00,               !- Complex Field #3
   0.0,                        !- Complex Field #4
   Until: 09:00,               !- Complex Field #5
   0.00181,                    !- Complex Field #6
   Until: 24:00,               !- Complex Field #7
   0.0,                        !- Complex Field #8
   Through: 12/31,             !- Complex Field #9
   For: Alldays,               !- Complex Field #10
   Until: 07:00,               !- Complex Field #11
   0.0,                        !- Complex Field #12
   Until: 09:00,               !- Complex Field #13
   0.00242,                    !- Complex Field #14
   Until: 24:00,               !- Complex Field #15
   0.0;                        !- Complex Field #16

SCHEDULE:COMPACT,
   PrecipitationAtlanta,       !- Name
   Any Number,                 !- ScheduleType
   Through: 1/1,               !- Complex Field #1
   For: AllDays,               !- Complex Field #2
   Until: 6:00,                !- Complex Field #3
   0.00105719,                 !- Complex Field #4
   Until: 7:00,                !- Complex Field #5
   0,                          !- Complex Field #6
   Until: 8:00,                !- Complex Field #7
   0.00105719,                 !- Complex Field #8
   Until: 24:00,               !- Complex Field #9
   0,                          !- Complex Field #10
   Through: 1/2,               !- Complex Field #11
   For: AllDays,               !- Complex Field #12
   Until: 24:00,               !- Complex Field #13
   0,                          !- Complex Field #14
   Through: 1/3,               !- Complex Field #15
   For: AllDays,               !- Complex Field #16
   Until: 24:00,               !- Complex Field #17
   0,                          !- Complex Field #18
   Through: 1/4,               !- Complex Field #19
   For: AllDays,               !- Complex Field #20
   Until: 6:00,                !- Complex Field #21
   0,                          !- Complex Field #22
   Until: 7:00,                !- Complex Field #23
   0.00105719,                 !- Complex Field #24
   Until: 24:00,               !- Complex Field #25
   0,                          !- Complex Field #26
   Through: 1/5,               !- Complex Field #27
   For: AllDays,               !- Complex Field #28
   Until: 24:00,               !- Complex Field #29
   0,                          !- Complex Field #30
```



```
   Through: 1/6,            !- Complex Field #31
   For: AllDays,            !- Complex Field #32
   Until: 13:00,            !- Complex Field #33
   0,                       !- Complex Field #34
   Until: 21:00,            !- Complex Field #35
   0.00105719,              !- Complex Field #36
   Until: 22:00,            !- Complex Field #37
   0,                       !- Complex Field #38
   Until: 23:00,            !- Complex Field #39
   0.00105719,              !- Complex Field #40
   Until: 24:00,            !- Complex Field #41
   0,                       !- Complex Field #42
   Through: 1/7,            !- Complex Field #43
   For: AllDays,            !- Complex Field #44
   Until: 24:00,            !- Complex Field #45
   0,                       !- Complex Field #46

SCHEDULE:COMPACT,
   HVACOperationSchd,                !- Name
   on/off,                           !- ScheduleType
   Through: 12/31,                   !- Complex Field #1
   For: Weekdays SummerDesignDay,    !- Complex Field #2
   Until: 06:00,                     !- Complex Field #3
   0.0,                              !- Complex Field #4
   Until: 22:00,                     !- Complex Field #5
   1.0,                              !- Complex Field #6
   Until: 24:00,                     !- Complex Field #7
   0.0,                              !- Complex Field #8
   For: Saturday WinterDesignDay,    !- Complex Field #9
   Until: 06:00,                     !- Complex Field #10
   0.0,                              !- Complex Field #11
   Until: 18:00,                     !- Complex Field #12
   1.0,                              !- Complex Field #13
   Until: 24:00,                     !- Complex Field #14
   0.0,                              !- Complex Field #15
   For: Sunday Holidays AllOtherDays,!- Complex Field #16
   Until: 24:00,                     !- Complex Field #17
   0.0;                              !- Complex Field #18

COMPACT HVAC:THERMOSTAT,
   termostato,          !- Thermostat Name
   ,                    !- Thermostat Heating Setpoint Schedule
   22,                  !- Thermostat Constant Heating Setpoint {C}
   ,                    !- Thermostat Cooling Setpoint Schedule
   24.5;                !- Thermostat Constant Cooling Setpoint {C}

COMPACT HVAC:ZONE:PURCHASED AIR,
   ZN10_Core_Space_2,   !- Zone Name
   termostato;          !- Thermostat Name
```

```
Report Variable,
   *,                                  !- Key_Value
   Surface Int Convection Heat Rate,   !- Variable_Name
   hourly,                             !- Reporting_Frequency
   HVACOperationSchd;                  !- Schedule_Name

Report Variable,
   *,                                  !- Key_Value
   Zone/Sys Sensible Cooling Rate,     !- Variable_Name
   hourly,                             !- Reporting_Frequency
   HVACOperationSchd;                  !- Schedule_Name

Report Variable,
   *,                                  !- Key_Value
   Purchased Air Sensible Cooling Rate, !- Variable_Name
   hourly,                             !- Reporting_Frequency
   HVACOperationSchd;                  !- Schedule_Name

Report Variable,
   *,                                  !- Key_Value
   Purchased Air Total Cooling Rate,   !- Variable_Name
   hourly,                             !- Reporting_Frequency
   HVACOperationSchd;                  !- Schedule_Name
```

3 Resultados

Foram procurados resultados sobre o desempenho médio das coberturas ao longo do verão e sobre o desempenho na hora de pico térmico das coberturas. Estes resultados basearam-se na simulação de uma cobertura com telha de fibro-cimento ao longo do verão em São Paulo, de 21 de dezembro à 21 de março, com schedule de chuva e irrigação. Foram simuladas três situações:

- Cobertura somente com telhas de fibro-cimento
- Cobertura com telha de fibro-cimento mais Ecotelhado
- Cobertura com telha de fibro-cimento mais camada de poliuretano

Os resultados são os seguintes, para valores ao longo do verão, para sistemas de ar condicionado operando das 7 às 22 h para dias de semana, das 7 às 18 para sábados e desligados aos domingos e feriados:

3.1 Cobertura somente com a telha:

Fluxo de calor médio ao longo do verão: 32,1 W/m²
Fluxo pico ao longo do verão: 127,2 W/m²
Data de ocorrência do pico: dia 2 de março, sexta-feira, às 13 h

3.2 Cobertura com telha e Ecotelhado:

Fluxo de calor médio ao longo do verão: 2,93 W/m²
Fluxo pico ao longo do verão: 11,9 W/m²
Data de ocorrência do pico: dia 26 de janeiro, sexta-feira, às 16 h

3.3 Cobertura com telha e poliuretano 50 mm:

Fluxo de calor médio ao longo do verão: 2,99 W/m²
Fluxo pico ao longo do verão: 13,3 W/m²
Data de ocorrência do pico: dia 29 de dezembro, sábado, às 14 h

Por estes resultados da simulação, o Ecotelhado equivale à uma camada de 50 mm de poliuretano.

ANEXO

Material:EcoRoof (EnergyPlus)

This definition must be used in order to simulate the green roof (ecoroof) model. The material becomes the outside layer in a green roof construction (see example below). In the initial release of the green roof model, only one material may be used as a green roof layer though, of course, several constructions using that material may be used. In addition, the model has only been tested with the CTF solution algorithm – a warning will be issued for other solution algorithm choices.

Field: Name

This field is a unique reference name that the user assigns to a particular ecoroof material. This name can then be referred to by other input data.

Field: Height of Plants

This field defines the height of plants in units of meters. This field is limited to values in the range 0.01 < Height < 1.00 m.

Field: Leaf Area Index

This is the projected leaf area per unit area of soil surface. This field is dimensionless and is limited to values in the range of 0.001 < LAI < 5.0.

Field: Leaf Reflectivity

This field represents the fraction of incident solar radiation that is reflected by the individual leaf surfaces. Solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths. Values for this field must be between 0.1 and 0.4.

Field: Leaf Emissivity

This field is the ratio of thermal radiation emitted from leaf surfaces to that emitted by an ideal black body at the same temperature. This parameter is used when calculating the long wavelength radiant exchange at the leaf surfaces. Values for this field must be between 0.8 and 1.0 (with 1.0 representing “black body” conditions).

Field: Minimum Stomatal Resistance

This field represents the resistance of the plants to moisture transport. It has units of s/m. Plants with low values of stomatal resistance will result in higher evapotranspiration rates than plants with high resistance. Values for this field must be in the range of 50.0 to 300.0.

Field: Name of the Soil Layer

This field is a unique reference name that the user assigns to the soil layer for a particular ecoroof. This name can then be referred to by other input data.

Field: Roughness

This field is a character string that defines the relative roughness of a particular material layer. This parameter only influences the convection coefficients, more specifically the exterior convection coefficient. A special keyword is expected in this field with the options being “VeryRough”, “Rough”, “MediumRough”, “MediumSmooth”, “Smooth”, and “VerySmooth” in order of roughest to smoothest options.

Field: Thickness

This field characterizes the thickness of the material layer in meters. This should be the dimension of the layer in the direction perpendicular to the main path of heat conduction. This value must be a positive.

Field: Conductivity

This field is used to enter the thermal conductivity of the material layer. Units for this parameter are W/(m-K). Thermal conductivity must be greater than zero.

Field: Density

This field is used to enter the density of the material layer in units of kg/m3. Density must be a positive quantity.

Field: Specific Heat

This field represents the specific heat of the material layer in units of J/(kg-K). Note that these units are most likely different than those reported in textbooks and references which tend to use kJ/(kg-K) or J/(g-K). They were chosen for internal consistency within EnergyPlus. Only positive values of specific heat are allowed.

Field: Absorptance:Thermal

The thermal absorptance field in the Material input syntax represents the fraction of incident long wavelength radiation that is absorbed by the material. This parameter is used when calculating the long wavelength radiant exchange between various surfaces and affects the surface heat balances (both inside and outside as appropriate). Values for this field must be between 0.0 and 1.0 (with 1.0 representing “black body” conditions).

Field: Absorptance:Solar

The solar absorptance field in the Material input syntax represents the fraction of incident solar radiation that is absorbed by the material. Solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths. This parameter is used when calculating the amount of incident solar radiation absorbed by various surfaces and affects the surface heat balances (both inside and outside as appropriate). Values for this field must be between 0.0 and 1.0.

Field: Absorptance:Visible

The visible absorptance field in the Material input syntax represents the fraction of incident visible wavelength radiation that is absorbed by the material. Visible wavelength radiation is slightly different than solar radiation in that the visible band of wavelengths is much more narrow while solar radiation includes the visible spectrum as well as infrared and ultraviolet wavelengths. This parameter is used when calculating the amount of incident visible radiation absorbed by various surfaces and affects the surface heat balances (both inside and outside as appropriate) as well as the daylighting calculations. Values for this field must be between 0.0 and 1.0.