THERMOSYPHON IN BUILDINGS: A SOLUTION FOR THERMAL BRIDGING

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ABSTRACT

Thermal bridging is a problem that arises from using a thermosyphon. It is used as a passive part of the building envelope in south facing walls. A solution is proposed and investigated in this paper. SolidWorks 2011 is used to simulate the thermal performance of the thermosyphon. A finite element analysis, FEA, (4 points Jacobian) is employed to measure the temperature and heat flux at different surfaces of the thermosyphon. Simulation results showed that the backward maximum heat flux reduces 76 times when a Teflon piece is introduced. As a result, this new design provides less heat loss due to thermal bridging.

INTRODUCTION

Thermal analysis on the thermo-diode panel has been investigated by many researchers (Chun et al., 2009) (Varga et al., 2002). Thermal analysis is the calculation of the temperature distribution in a body due to conduction, convection, and radiation. By thermodynamics laws, heat energy flows from the higher temperature medium to the lower temperature medium. Heat transfer by conduction and convection needs media, while heat transfer by radiation is independent (Incropera & De Witt, 2002).

Analysis is the key to effective design. Analysis is performed for, but not limited to:

- Deformations/strains and internal forces/stresses
- Temperatures and heat transfer in solids/fluids
- Fluid flows with or without heat transfer
- Conjugate heat transfer between solids and fluids

In engineering practice, analysis is conveniently performed with the use of finite element computer programs (e.g. SolidWorks, ANSYS, ANIDA, NASTRAN, etc). The finite element method is being used in every engineering discipline. Aerospace, automotive, biomedical, chemicals, electronics, energy, geotechnical, manufacturing, and plastics industries routinely apply finite element analysis. In addition, it is not only used for analyzing classical static structural problems, but also for such diverse areas as mass transport, heat transfer, dynamics, stability, and radiation problems. Finite element analysis is the method of choice for optimizing new designs, verifying the fitness of existing facilities, predictive performance and evaluating new concepts. Accuracy of FEA solutions should always be assessed. If the mesh size is fine enough, an accurate solution is expected. (Cook et al., 2001).

"Thermal diode" or "thermo-diode" refers to a thermal system component that allows heat transfer only in the desired direction, but blocks the flow of heat in the opposite direction. The terms ''thermo-diode" and ''thermal diode" were used interchangeably in the past. However, in recent years a thermal diode has been commonly used for thermionic or thermoelectric devices that generate electricity directly from heat (Chun, et al., 2009). A two-phase thermosyphon is a passive thermo-diode (TD) enclosure that transfers heat against gravity (forward direction) and the condensate moves back by the gravity (backward). It is composed of three sections: evaporator, adiabatic, and condenser. Thermosyphons are currently being used successfully in solar water heaters (Thirugnanasambandam et al., 2010). This suggested design reduced the building's dependency on fossil fuel energy. Recently, utilization of the TD has received much interest in research to reduce energy demand and to enhance the performance of building envelopes (Varga et al., 2002). TD has potential applications for energy efficiency of buildings to transfer thermal energy from incident solar radiation and conduct it through the panel to the building structure during the heating season. It also acts as an insulating material and reduces heat loss when the building structure is at a higher temperature than the external surface. Conveniently, TD is incorporated into a panel as shown in Figure 1. This combination is called a thermo-diode panel (TDP). Experimentally, forward heat transfer is found to be three to five times greater than backward heat transfer (Varga et al., 2002). The performance of the two-phase thermosyphon as thermo-diode is well known (Zohuri, 2011); (Faghri, 1995); (Reay & Kew, 2006); (Chi, 1976). Additionally, in comparison to glazing and other passive solar heaters (e.g., vertical plates, honeycomb sheets, and inclined sheets), its performance was supperior (Bahr & Piwecki, 1981).

Researchers always reported unwanted heat loss due to the thermal bridging effect of the copper pipe walls (Varga et al., 2002). The preliminary investigation of the TDP integrated with phase change materials (PCM) shows that it can be used to transfer solar energy into the buildings in Toronto (Poulad & Fung, 2012). As the temperature may be extremely cold in Toronto in winter, thermal bridging might be an issue, which is worth investigating.

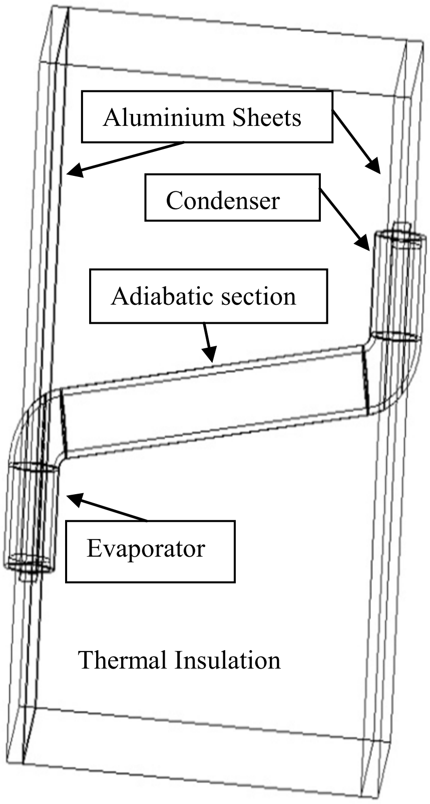

Figure 1 Sketch of the TDP components, evaporator is subjected to solar radiation and condenser is inside the home/zone

In order to investigate thermal bridging, backward thermal conductivity of the thermosyphon should be determined. It can be calculated either exactly, based on the analytical solution of the heat conduction equation, or by approximation, based on a numerical solution of the heat transfer. The former is limited to situations where analytical solutions exist. The most common approximation techniques are finite element analysis (FEA) (Segerlind, 1984), and electric circuit analogy (Incropera & De Witt, 2002).

METHODOLOGY

Exact solution

During thermal bridging, fluid is condensed in the evaporator (outside), and heat passes through the adiabatic section of the thermosyphon, which is the copper pipe. In this case, indoor temperature is higher than outdoor temperature; therefore, heat flows/leaks from indoor to outdoor through the most thermal conductive part of the TDP (i.e., copper). Figure 2 shows the sketch of this section with its electric circuit analogy. T_o and T_i are outside and inside temperatures of the zone where the panel is installed on its wall. Teflon is inserted in the middle of the copper pipe to disconnect, thermally conductive copper pipes. The insert has a hole same size as the copper pipe; therefore, it does not impede flow of water vapor to transfer heat from the two ends. The length of each copper section and Teflon is L and l, respectively.

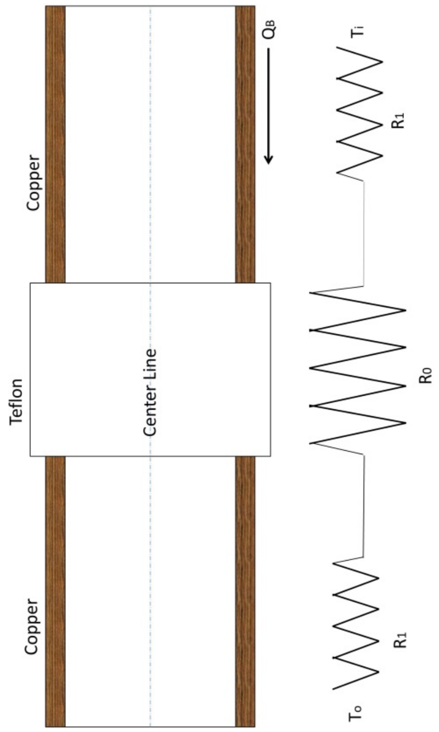

Figure 2 Sketch of the adiabatic section of the thermosyphon with its electric circuit network

The total thermal resistance in the backward direction is calculated with the following assumption:

- Steady state one dimension heat flow (only along the pipe)
- Negligible contact resistance and thermal conductivity of water vapor inside the pipe
- Isotropic thermal properties for copper and Teflon
- Constant temperature on both ends (-20℃ outside and 20℃ inside)

Therefore,

$$R = \sum R_i = \frac{2L}{k_1 A_1} + \frac{l}{k_0 A_0} \quad (1)$$

$$Q_B = \frac{\Delta T}{R} \quad (2)$$

as ΔT is constant for two cases:

$$Ratio = \frac{Q_{B,c}}{Q_{B,n}} = \frac{\frac{2L}{k_1 A_1} + \frac{l}{k_0 A_0}}{\frac{2L+l}{k_1 A_1}} = \frac{2L}{2L+l} + \frac{l k_1 A_1}{2L k_0 A_0} \quad (3)$$

where k, Q, L, l, and A are thermal conductivity, heat transfer, half of the copper length, Teflon piece length, and cross section area, respectively. Subscripts 1, 0, B, c, and n refer to copper, Teflon, backward, conventional design and suggested/new design, respectively.

Conventional design does not have the second term ($\frac{l}{k_0 A_0}$) of Eq. (1); therefore the ratio, in Eq. (3), is always bigger than one because the first fraction ($\frac{2L}{2L+l}$) is close to one and $\frac{k_1}{k_0}$ is much bigger than $\frac{lA_1}{2LA_0}$. For the values given in Table 1, the ratio in Eq. (3) is about 76. Obviousely, A is $\pi(r_o^2 - r_i^2)$.

Table 1
Values of the parameters used in Eq. (3). Lengths, areas and thermally conductivities are in mm, mm², and W/mK, respectively. Subscripts I and O refer to inside and outside radius

k_1	A_1	k_0	l	L	RATIO
390	263.76	0.25	10.6	35.1	75.80
r_{i1}	r_{o1}	r_{i0}	r_{o0}	A_0	
12.5	15.5	12.5	20.5	828.96	

To make the backward heat transfer ($Q_{B,c}$) as low as possible, the thermal conductivity of the new coupling (k_0) should be minimized. To find the right coupling material, a decision matrix was devised (Table 2). Seven low thermal conductivity (<0.5 W/mK) materials, which are available in the market, were investigated for selecting the best option. Ten important characteristics were ranked from 1 (the least important) to 10 (the most important). Each material was scored from 1 (the worst) to 10 (the best) for that characteristic. Finally, the total score can be calculated as follows:

$$Total = \sum_{i=1}^{10} (Rank * Score)_i \quad (4)$$

As shown in Table 2, Teflon had the maximum total score, 546, and was selected as a coupling material for this design. Based on the selection and the panel dimensions, Table 1 is produced.

Thermal simulation results

To determine the thermal properties of the TDP, a finite element analysis, FEA, (4 points Jacobian) is employed using SolidWorks 2011. In backward direction thermal analysis, the inside and outside temperatures of the building are fixed to 20℃ and -20℃, respectively. The mesh quality is selected as high with maximum and minimum element size of 15mm and 3mm, respectively. In forward direction analysis, a constant insolation of 500 W/m², ambient temperature of -20℃, emissivity of 0.97 with a free convective heat transfer coefficient of 20W/Km² is considered on the radiated surface. Inside temperature was fixed to 20℃. In the forward direction, the thermosyphon is defined as a new material in the SolidWorks library with thermal conductivity equal to calculated value for the thermosyphon of the same size (0.00042K/W) (Poulad & Fung, 2012). In the backward direction, the thermal conductivity is calculated based on the thermal specifications of the materials in the drawing.

Conveniently, a thermosyphon is made of a sealed copper pipe with water (as fluid) inside. The modified design considers a Teflon coupling between the two ends of copper parts to reduce thermal bridging.

The problem domain is subdivided into 267,411 nodes and 188,025 tetrahedron (triangular base) elements. Static analysis and the FFEPlus[1] solver with a mesh size of 3 to 8mm (with no distortion and high quality) is employed (Figure 3).

Figure 3 Sketch of the mesh on the TDP

Based on SolidWork simulation, roughly, the ratio of the backward heat flux for the current design and the suggested one is about 80 (Figure 4). To find the approximate ratio, the heat flux on similar sections on the new design are divided to the current/old ones.

To obtain a more accurate ratio than the above value (80), the heat flux at the cross section of the similar length (L) of the two designs was investigated (see

[1] The FFEPlus solver is an iterative solver. After having the CAD model set up with the appropriate boundary conditions, the FFEPlus solver makes an educated guess about the deformation, [U], of the model. Then it evaluates the matrix equations to see how good the guess was, and adjusts the deformation accordingly, depending upon the error in the calculation. This process repeats until the calculation balances.

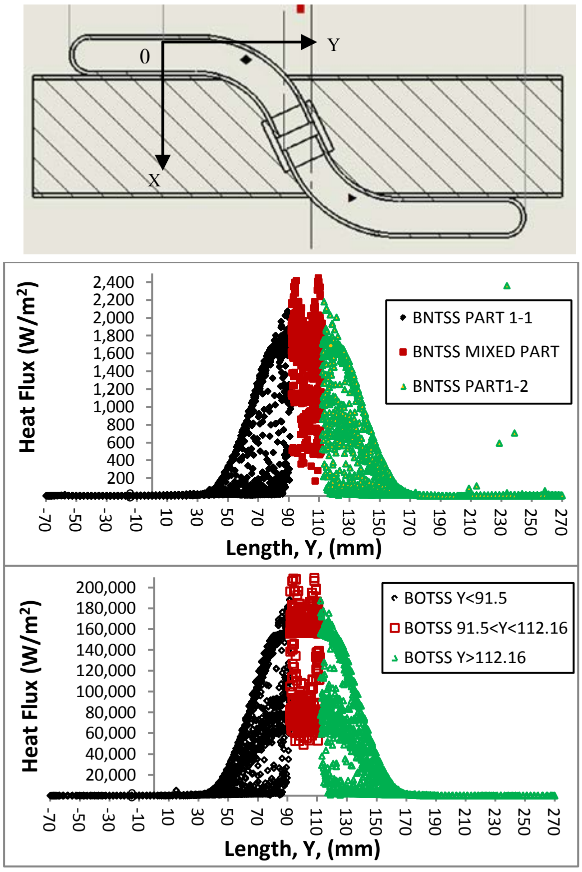

Figure 4 Heat flux distribution at different length (Y-value) of the thermosyphon. The top sketch shows the location of the heat flux measurement, the middle graph represents the new design backward heat flux (BNTSS), and the bottom graph shows the current/old design backward heat flux (BOTSS). In the middle graph, PART 1-1 and 1-2 are the cupper pieces around the Teflon piece (MIXED PART)

Figure 5 and 6). The sections are selected consistent with the values given in Table 2. Twelve different elements on each section were selected and their heat flux extracted from simulation results.

Table 3
Backward heat flux (W/m^2) statistics for 12 nodes on each section

		NEW DESIGN	OLD DESIGN	RATIO
INDOOR SIDE	Average	421	38509	91.4
	Max	703	63800	90.8
	Min	88.7	5710	64.4
	STDEV	194.7	18901	
	COV	0.46	0.49	
OUTDOOR SIDE	STDEV	194.4	17919	
	COV	0.42	0.47	
	Max	720.3	65540	91
	Min	129.3	5449	42.1
	Average	464.9	38311	82.4

The coefficient of variation (COV = STDEV/Average) of the heat flux values is found to be about 0.45 (see Table 3), which means the average is not a good representative of the heat flux. As ratio values on Table 3 stipulate, the ratio is between 42 and 91. It is interesting that the average value of the maxima (90.8 & 91) and minima (64.4 & 42.1) on Table 3 is 72.1, which is slightly lower than the exact value calculated from Equation (3), 75.8. The difference is only 4.9%, which is reasonable.

Displacement/strain results of simulation

In this section, the displacement or strain due to the thermal stress is analysed for the new design. In this analysis, the forward heat transfer is simulated with the same solver as the thermal analysis. In addition, the thermal loads on the evaporator surface are as follows:

Convection coefficient	2W/K.m^2
Bulk ambient temperature	20°C
Ambient/sky temperature	20°C
Emissivity	0.97
View factor	1
Constant heat flux	1000W/m^2
Indoor temperature	20°C

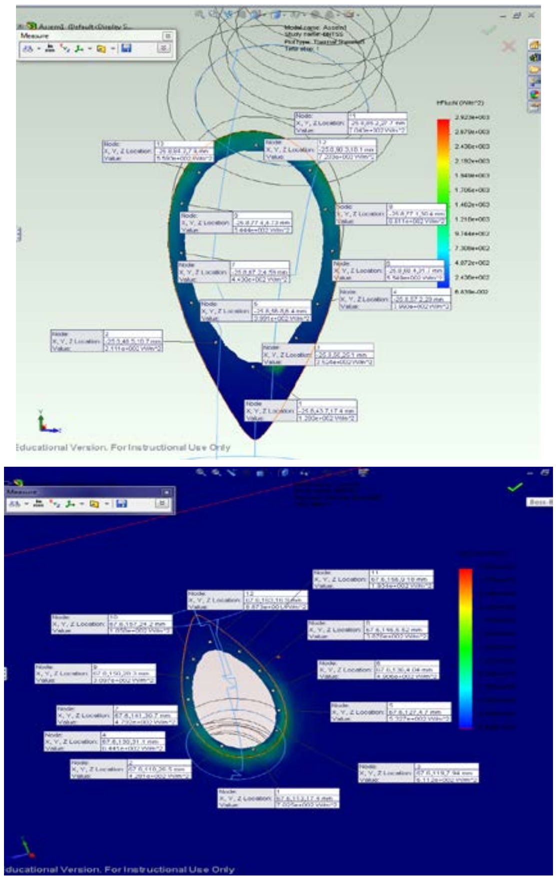

Figure 5 Heat flux distribution at different points of the cross section (same Y-value) of the new/suggested design in backward direction. The pictures show the heat flux at y = 60mm (top) and y = 140mm (bottom)

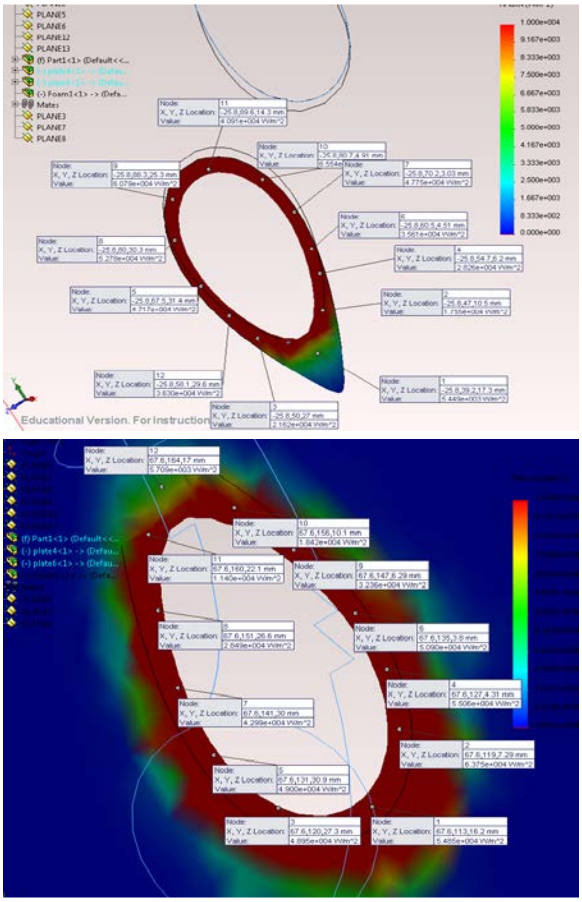

Figure 6 Heat flux distribution at different points of the cross section (same Y-value) of the current design in backward direction. The pictures show the heat flux at y = 60mm (top) and y = 140mm (bottom)

The results of thermal analysis are transferred for displacement analysis. The results show that the displacement of the Teflon part is compatible with the other connected copper parts (Figure 7). The maximum resultant displacement and strain are found to be 0.026mm and 0.0007, respectively.

RESULTS AND DISCUSSION

Thermal bridging can be reduced by about 76 times using a Teflon part in the middle of the thermosyphon structure (Figures 2 and 7). Thermal bridging occurs in the backward (unwanted) direction when the indoor temperature is higher than the outdoor temperature in current TDPs. As this panel is supported by a south wall, there is no external mechanical/physical stress on it; therefore, thermal load is the only source of stress on the thermosyphon. The thermal stress analysis in severe conditions (see the previous section) on the Teflon part (the weakest part, mechanically) shows that the maximum resultant strain is less than 0.1%. At this strain level, all polymers are safe and in the elastic limit (Hayden et al., 1965). It appears that the average of extrema is closer to the exact solution than the arithmetic average value. This will be the focus of future investigation.

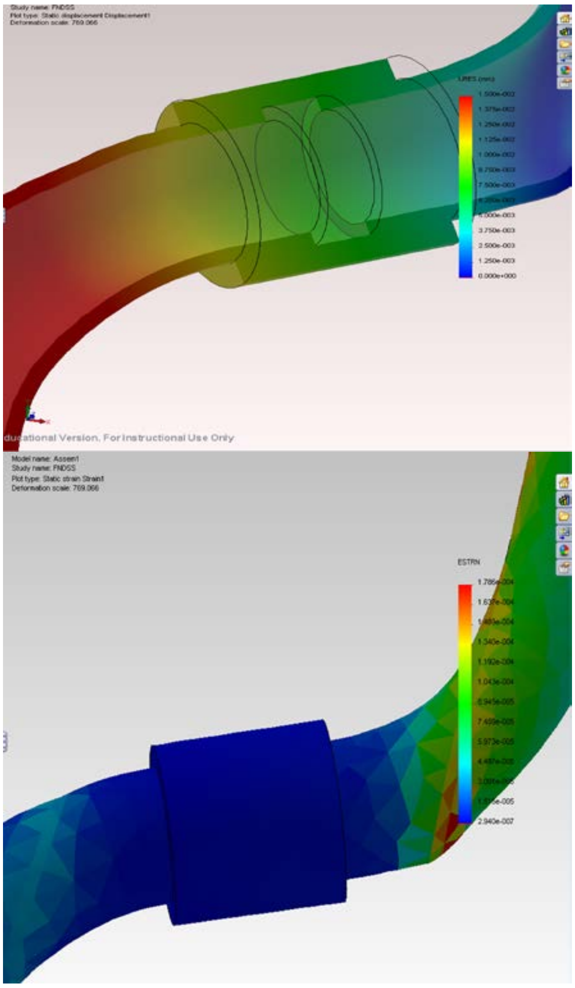

Figure 7. Displacement (top) and strain (bottom) distribution of the new design parts (Teflon and cupper parts attached to it) in the forward heat transfer condition

CONCLUSION

The performance of a typical thermosyphon is simulated with SolidWork 2011. The thermal bridging effect of adding a piece of Teflon in the thermosyphon assembly is investigated and compared with the conventional design (one piece of copper sealed tube containing fluid). The thermal bridging is investigated on a typical winter day (indoor temperature and outdoor temperature are considered 20℃ and -20℃, respectively). The results show that the backward heat transfer can be reduced 76 times by adding a piece of Teflon in the current thermosyphon assembly.

FUTURE WORK

Although simulation results are reasonably close to the exact value, results (exact solution and simulation) need validation (experimental verification). The process of making a prototype is under way. Then, experiments will be carried out.

NOMENCLATURE

A area, mm^2

BNTSS	backward, new/suggested design and steady state thermal analysis
BOTSS	backward, old/current design and steady state thermal analysis
COV	coefficient of variation, STDEV/average
FEA	finite element analysis
l	Teflon part length, mm
L	cupper part length, mm
k	thermal conductivity, W/mK
Max	maximum
Min	minimum
r	radius, mm
R	thermal resistance, K/W
STDEV	standard deviation, $\frac{\sqrt{\sum(x-\bar{x})^2}}{n}$
Q	heat flux, W/m^2
T	temperature, K
TD	thermo-diode
TDP	thermo-diode panel
Wt	weight

Greek letter

Δ	difference

Subscripts

0	Teflon properties
1	cupper properties
B	backward direction
c	current/old design
i	indoor/inside
n	new/suggested design
o	outdoor/outside

Superscript

*	reference condition

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REFERENCES

Bahr, A. & Piwecki, H., 1981. *Passive solar heating with heat storage in the outside walls,* Ispra Establishment, Italy: Commission of the European Communities.

Chi, S. W., 1976. *Heat Pipe Theory and Practice, A Sourcebook.* Washington: Hemisphere Publishing Co..

Chun, W. et al., 2009. Effects of working fluids on the performance of a bi-directional thermodiode for solar energy utilization in buildings. *Solar Energy,* p. 83 409–419.

Cook, R. B., Malkus, D., Plesha, M. & Witt, R., 2001. *Concepts and Applications of Finite Element Analysis.* 4 ed. s.l.:John Wiley & Sons.

Faghri, A., 1995. *Heat pipe science and technology.* Washington: Taylor & Francis.

Hayden, H., Moffatt, W. & Wulff, J., 1965. *The Structure and Properties of Materials, Volume III.* New York: John Wiley & Sons.

Incropera, F. P. & De Witt, D. P., 2002. *Introduction to Heat Transfer, 4th Ed..* New York: John Wiley & Sons.

Poulad, M. E. & Fung, A. S., 2012. *Potential benefits from Thermosyphon-PCM (TP) integrated design for buildings applications in Toronto.* Halifax, NS, e-Sim Conference proceedings, Dalhousie University.

Reay, D. & Kew, P., 2006. *Heat Pipes : Theory, Design and Applications (5th Edition).* Jordan Hill, UK: Butterworth-Heinemann.

Segerlind, L., 1984. *Applied Finite Element Analysis.* New York: Wiley.

Thirugnanasambandam, M., Iniyan, S. & Goic, R., 2010. A review of solar thermal technologies. *Renewable and Sustainable Energy Reviews ,* p. 14 312–322.

Varga, S., Oliveira, A. O. & Afonso, C. F., 2002. Characterization of thermal diode panels for use in the cooling season in buildings. *Energy and Buildings,* pp. 34, 227-235.

Zohuri, B., 2011. *Heat Pipe Design and Technology.* Boca Raton, FL: CDC Press, Taylor & Francis Group.

Table 2
Coupling material decision matrix

	COMPLETE NAME			POLYAMIDE 6		POLYAMIDE - IMIDE		POLYACÉTAL-COPOLYMÈRE		POLYÉTHILÈNE TRÈS HAUTE DENSITÉ		POLYTÉTRAFLUORE		POLYESTER THERMO-PLASTIQUE		POLYÉTHERETHÉRCETONE	
	BRAND NAME			**AKULON - NYLON - ERTALON**		**TORLON**		**ERTACETAL - DELRIN**				**TEFLON**		**ARNITE - ERTALYTE**			
		UNIT	**WT**	**VALUE**	**SCORE**	**VALUE**	**SCORE**	**VALUE**	**SCORE**	**VALUE**	**SCORE**	**VALUE**	**SCORE**	**VALUE**	**SCORE**	**VALUE**	**SCORE**
MECHANICAL CHARACTERISTICS	Density	gr/cm^3	2	1.14	9	1.41	6	1.42	6	0.96	10	2.2	5	1.37	7	1.32	8
	Saturated water absorption	%	3	1.8	4	2.5	3	0.25	8	0.01	10	0.01	10	0.25	8	0.3	7
	Tensile strength	N/mm^2	8	78	7	120	10	65	6	24	3	27	3	74	7	92	8
	Corrosion Resistance		10	Bad	3	good	7	good	7	good	7	Excellent	10	good	7	Very good	9
THERMAL CHARACTERISTICS	Coefficient of linear expansion	$10^{-6}/°C$	10	70	7	30	10	100	6	200	3	100	6	70	7	70	7
	T_{max}	°C	10	100	3	250	9	100	4	80	2	260	10	100	3	250	9
	T_{min}	°C	2	-40	10	-200	10	-40	10	-100	10	-200	10	-20	7	-60	10
	Thermal conductivity	W/m°C	8	0.23	9	0.4	6	0.31	8	0.43	6	0.23	9	0.21	10	0.25	9
OTHERS	Cost		10	low	8	high	2	low	8	low	8	Medium	5	low	8	high	2
	Manufactu-rability		8	good	7	bad	3	Excellent	10	Medium	6	Excellent	10	Good	7	Good	7
	Total				444		473		498		390		**546**		494		519