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Peltier cells based acclimatization system for a container passive building

Michele Trancossi[1*], Jacob Kay[2], Mauro Cannistraro[3]

[1] Sheffield Hallam University, Sheffield UK, Cedita-Romaero, Bucarest, RO
[2] Sheffield Hallam University, Sheffield UK, ACES Student
[3] Department of Architecture, University of Ferrara, Italy

Corresponding Author Email: mtrancossi@gmail.com

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ABSTRACT

This paper analyses the hypothesis of using Peltier cells based heat pumps for the acclimatization of a real building. It define a possible design of a low cost reversible heat pump that allows combined heating and cooling of an high energy efficiency container house with a low emissions envelope. The climatic location has been indicated in Bologna (Italy). A complete and exhaustive mathematical model has been defined. The plant has been accurately designed by considering real industrial components. In particular, a preliminary dimensioning have been produced It clearly demonstrates that this plant can couple efficiently with a photovoltaic energy plant because of the seasonal distribution of consumption between heating and cooling needs.

1. INTRODUCTION

Thermoelectric coolers (TECs) convert electrical energy into thermal energy. When electricity circulates they generate a small temperature gradient. This effect is usually presented as ‘Peltier Effect’. They have assumed an effective importance for application that requires to cool the electronic circuits and processors, and to produce an accurate temperature control for precise devices. Alternatively the can be used as electrical temperature measurement systems and small cogeneration units from thermal sources.

Riffat and Ma [1] have produced a fundamental review of thermoelectric devices and their fundamental applications in different fields of applications. They realize a conversion between electric energy and thermal energy. Their evident advantage is the absence of noise and vibration, because they have no moving part, they are small-sized and lightweight. They ensure an effective, but small scale refrigeration capacity without the necessity of using dangerous (i.e. ammonia) or environmentally relevant gasses (i.e. CFC). The authors observe that the simplicity and the intrinsic affordability allow a large range of applications.

A Peltier element is a thermoelectric heater/cooler that acts like a micro heat pump. It is based on Seebeck effect. Two dissimilar metals connected at two different junctions create a micro-voltage when the junctions are hold at different temperatures [2]. In addition, Peltier demonstrated that thermocouples produce a temperature difference ΔT between the junctions when an electric current flows inside the thermocouple. Heating or cooling effect of the junction is created depending on the direction of the current. The relation between the temperature change and the current has been demonstrated by Lord Kelvin.

It is evident that a Peltier cell ensures two different actions:

(1) Heating / Cooling - When an adequate current crosses Peltier cells, they act as refrigerator on one side and heater on the other. It appears evident that Peltier cells produce a cooling effect without compression and consequent noise.

(2) Cells for electric cogeneration - When Peltier cells are thermally excited, they generate electric voltage, which is proportional to the temperature difference. Electric generators may either consist of a single Peltier cell or a group of them.

(3) Chein and Huang [3] have tested Peltier cells for the temperature control of lasers.

Homer, Riffat and Ma [4] produced an effective investigation on the use of phase change materials (PCMs) integrated with thermosyphons in a thermoelectric refrigeration system. By mean of a changing state element, the proposed cooler demonstrated excellent performance and some storage capability, when coupled with a Peltier cell as a cold sink which is coupled with a thermal diode to allow heat flow in one direction only.

Thermoelectric small-space air conditioners have been investigated Gillott, Jiang and Riffat [5]. They have analyzed and tested a thermoelectric cooler, which has been specifically designed for small-scale space conditioning in buildings. They have sandwiched TE modules between aluminum heat sinks. In particular, the heat sinks are cooled on the heat side by mean of small computer fans to ensure force convection. Air in the cold side has been forced through the heat exchanger by a blower.

Peltier cells based TE modules can be used for air conditioning inside the so called Active Building Envelopes [6] or ABEs. These systems use a renewable source of energy to heat or cool the building by direct or indirect methods. The adoption of Peltier cells into ABEs is usually integrated into enclosure surfaces. They can operate on both heating and cooling mode depending on the direction of the current.

Xu and Van Dessel [7] present an ABE that use solar energy to keep a temperature gradient across a surface of the envelope by compensating for the passive heat transfer through walls with heat transfer from the TE system. The have produced several testing campaigns in different conditions. By an integrated system that uses PV cells connected to a heat pump based on Peltier cells, the heat flow across a surface of the building can be controlled. Xu and Van Dessel [8] have realized applications consist of multiple Peltier cells integrated on two aluminum tubes placed on both sides of a window. This application has been connected with a photovoltaic electric generator and a battery for energy storage. They obtained interesting results: ΔT=2÷6°C, overall efficiency = 11%, cooling efficiency 5%, heating efficiency 13%.

2. PELTIER CELLS MODEL

2.1 General model of the Peltier cells

Figure 1 shows the typical layout of a Peltier cell working as a refrigerator.

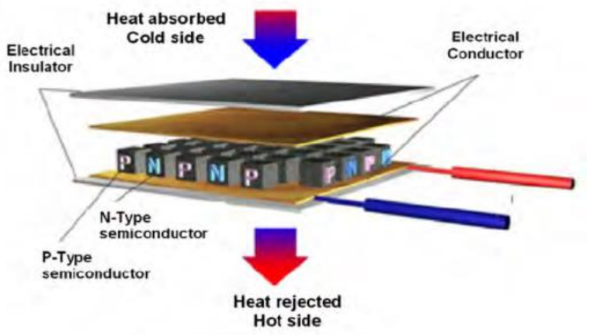


Figure 1. Sketch of a Peltier module working as refrigerator (Astrain and Martinez [9])

A Peltier element is characterized by positive and negative semiconductors placed between two conductive plates (usually copper). When a continuous current circulates, it generates a heat flow and a temperature difference between the two plates.

Manella et al. [10] present the general equation of the Peltier effect:

$$\dot{Q} = \alpha \cdot T \cdot I \tag{1}$$

In which Q is the heat power, α the Seebeck coefficient, T the temperature and I the current.

Cosnier et al. [11] observes that Peltier cells are constituted by an array of Bismuth and Telluride pellets which are electrically connected in series, but thermally connected in parallel. If a direct current [12] is applied one side of the cell absorbs heat (cold side) and the other side supplies heat (hot side). In this way, the thermoelectric generator produces a temperature difference between both sides of the module as displayed in Figure 1.

When two isotropic semiconductors are linked and a temperature difference, ΔT is applied between the junction and the two ends (which are kept at the same temperature), a voltage potential, V, will appear. The differential Seebeck coefficient, α, is consequently defined as:

$$\alpha = \frac{V}{\Delta T} \tag{2}$$

which is positive if the electromotive force drives the current from the hot to the cold junction.

It is also possible to define the Peltier coefficient, π

$$\pi = \frac{\dot{q}}{I}\,. \tag{3}$$

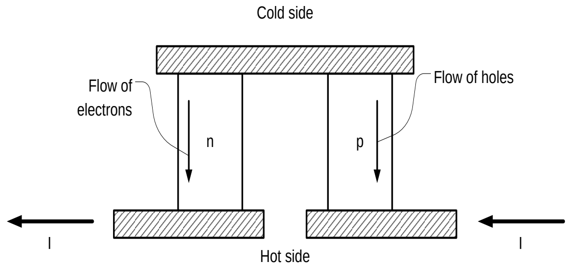


Figure 2. Principle of a Peltier cell

It is then possible to express the Peltier coefficient as a function of the Seebeck one.

$$\pi = \alpha T \tag{4}$$

In consequence, it is possible to express equation (1)

$$\dot{Q} = \alpha T I = \pi I \tag{5}$$

Thompson effect can be defined by considering an electric current I, which flows in a homogeneous conductor in the direction of a temperature gradient dT/dx. In this case heat can be produced or absorbed according to equation (6).

$$P_T = \tau I \frac{dT}{dx} \tag{6}$$

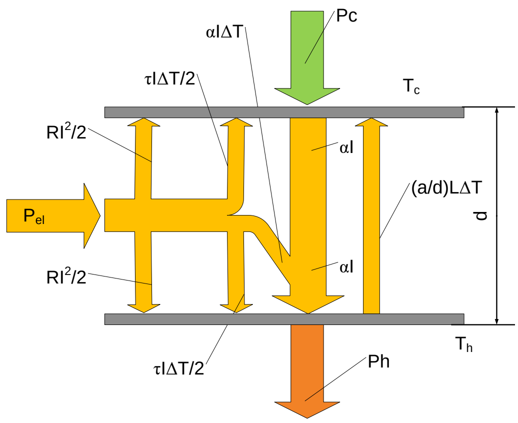


Figure 3. Energy flow in a Peltier cell (p_t>0)

2.2 Thermoelectric heat pumps

If we consider an electric current I, that flows in an isothermal conductor of resistance R, we have the Joule effect:

$$P_J = R \cdot I^2 \tag{7}$$

Because of heat conduction, heat also flows from the hot side (temperature T_h) to the cold side (temperature T_c):

$$P_L = L\frac{A}{d}\cdot(T_H - T_C) \tag{8}$$

where L is the conductivity, A the cross-sectional area and d the thickness of the Peltier component.

Jugsujinda et al [13] assume $\Delta T = T_H - T_C$ and calculate the energy balance of the system (Figure 3):

heat flux on the cold side (the cooling capacity)

$$\dot{Q}_C = -P_C = \alpha I T_C \pm \frac{\tau I \Delta T}{2d} - \frac{I^2 R}{2} - \frac{L A \Delta T}{d} \tag{9}$$

heat flux on the cold side (the cooling capacity)

$$\dot{Q}_H = P_H = \alpha I T_H \pm \frac{\tau I \Delta T}{2d} + \frac{I^2 R}{2} - \frac{L A \Delta T}{d} \tag{10}$$

electrical power

$$P_{El} = \alpha I \Delta T \pm \frac{\tau I \Delta T}{2d} + I^2 R = U_p I_p \tag{11}$$

The above terms allow determining the cooling efficiency of the system:

$$\eta_C = \frac{P_C}{P_{el}} = \frac{P_H}{U_P I_P} \tag{12}$$

and the heating one:

$$\eta_H = \frac{P_H}{P_{el}} = -\frac{P_H}{U_P I_P} \tag{13}$$

As Goldsmid [2] states, this schema allows using a manageable current and an acceptable voltage drop. Thermoelectric refrigeration is based on Altenkirck's model. Goldsmid and Douglas [14] verify Altenkirck's model. If thermal resistance between the thermocouple and the sink, radiating dissipation and electric losses are negligible, it is possible to determine the heat factors, which are the ideal efficiencies of a Peltier thermocouple:

$$e_C = \eta_c = \frac{T_C}{T_H - T_C} \tag{14}$$

$$e_H = \eta_H = \frac{T_H}{T_H - T_C} \tag{15}$$

in which T is the absolute temperature of the source, H, and the sink, C.

3. DESIGN OF A REVERSIBLE HEAT PUMP BY COUPLED SOLAR AND PELTIER CELLS

Figure 4 presents the schema of a prototype of a reversible air treatment system based on Peltier cells, which has been studied successfully by Le Pierres et al. [15].

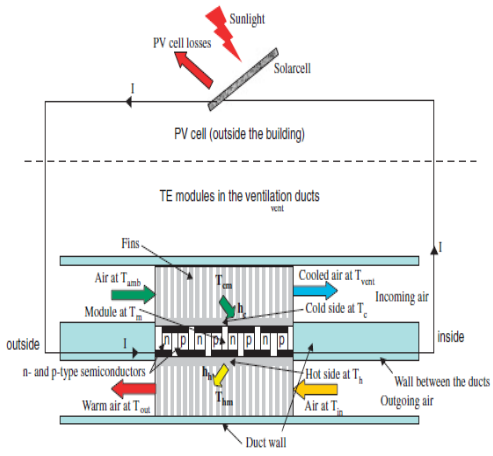


Figure 4. The Peltier cell air conditioning system studied by le Pierrés et al. [15]

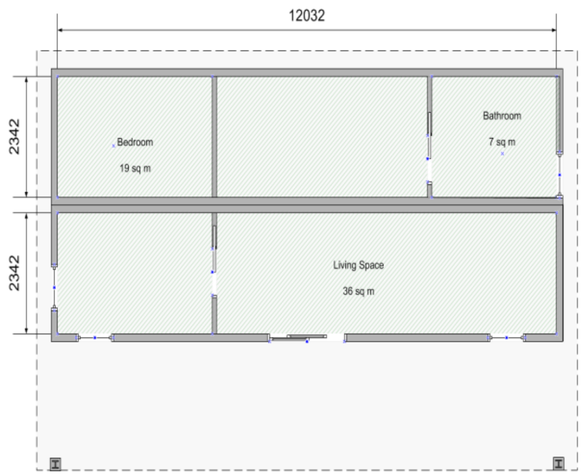


Figure 5. Container house plant drawing [16]

4. BUILDING ENERGY NEEDS

This paper consider the use of the realization of a container house made of two container units (Figure 5) with a forced ventilation system, and acclimatization ensured by Peltier cells according Le Pierrés.

The container house is considered having the plant presented in Figure 6. The energy performance has been evaluated by assuming the location of Bologna (Italy). The reference building assumed is the one adopted by Trancossi and Pascoa [16], with an internal insulation by vacuum insulated panels (VIP)/foam combination have been assumed for exterior walls. In line with the deductions by Bowley, VIP panels can be layered with half inch foam board on either side.

In particular, Turvac FG [17] silica vacuum insulated panels has been assumed as a reference material. 40 mm insulation has been assumed. The composition of the layered wall has been presented in Table 1.

It can be observed that use of VIC allows reducing the thickness to maximum 67.5 mm. It ensures to minimize the losses in terms of space due to the external walls. Double glassed windows with Argon gas have been assumed with a U value in the range 0.7÷1.1W/(m^{2}K) [18] a model with 0.8 W/(m^{2}K) has been adopted.

Table 1. Properties of wall layers [16]

n.	Mat.	*S* [mm]	*ρ* [kg/m³]	*K* [W/(mK)]	*A* [W/(m²K)]	*C* [J/kgK]
	Ext.				25	
1	Steel	1	8000	17		500
2	PU	12.5	40	0.022		1600
3	VIC	20÷40	180	0.0041		500
4	PU	12.5	40	0.022		1600
5	Steel	1	8000	17		500
	Int.				7.7	
Overall heat transfer coefficient				0.16÷0.09 W/(m²K)		

Table 2. Building external surfaces geometry and emissions

	Gross Area	Wall	Heat flux	Window	Heat flux
	[m2]	[m2]	[W]	[m2]	[W]
South	31.59	25.11	56.7÷102.0	6.48	113.0÷178.0
North	31.59	31.59	71.4÷128.0	0.00	
East	12.63	11.37	21.8÷46.0	1.26	25.2÷31.4
West	12.63	11.37	21.8÷46.0	1.26	25.2÷31.4
Area	88.45	79.45		9.00	

Building energy performance has been evaluated by Certificare 1.0 [19] energy performance software by Trancossi and Pascoa.

Table 3. Building energy initial performance (Winter)

Heating	Jan	Feb	Mar	Apr	Oct	Nov	Dec	
Transmission dispersions	162,3	127,3	100	28,6	29,1	102,6	146,1	kWh
Ventilation dispersions	181,0	140,7	107,2	28,4	28,3	110,6	161,8	kWh
Internal contribution	184,5	166,7	184,5	89,3	101,2	178,6	184,5	kWh
Solar contribution	104,2	131,7	174,2	77,1	91,2	115,3	98	kWh
Net energy Needs	55,4	2,4	0	0	0	0	28,9	kWh
Heating need	*17.5*	*kWh/m²*	*CO_2 emissions*		*2.75*	*$kgCO_2/m^2$*		

Table 4. Building performances during summer

Cooling needs	May	Jun	Jul	Aug	Sep	kWh
Transmission dispersions	73,7	36,0	17,6	23,2	53,0	kWh
Ventilation dispersions	76,0	31,6	9,4	16,1	51,8	kWh
Internal contribution	184,5	178,6	184,5	184,5	178,6	kWh
Solar contribution	202,3	203,3	223,4	214,2	216,1	kWh
Net energy Needs	237	314,5	381	359,2	289,9	kWh
Cooling need	*36.0*	*kWh/m²*	*CO_2 emissions*	*5.95*	*$kgCO_2/m^2$*	

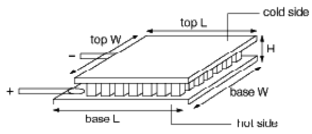
As Trancossi and Pascoa have observed, the energy performance during winter is excellent. Otherwise it looks worst during summer and also water heating performance can be improved.

5. EXTIMATION OF PELTIER CELL ACCLIMATIZATION PLANT

The evaluation of energy needs for acclimatization has been estimated by assuming a Ferrotech 72005/128/060B. Peltier cell [20]. It has been adopted Thermal Cycling Thermoelectric Module which is specifically designed for temperature cycling applications. They have better resistance to demanding physical stresses as the module shifts from heating to cooling and a longer operative life in terms of number of cycles during the operational life.

Table 5. Ferrotech 72005/128/060B technical specifications

Base W (mm)	39.7		
Base L (mm)	42.8		
Top W (mm)	39.7		
Top L (mm)	39.7		
Height (mm)	3.94		
Performances at 50°C			
I Max (A)	6.0	ΔT Max (°C)	83.0
V Max (V)	18.2	Qc Max (W)	57.0



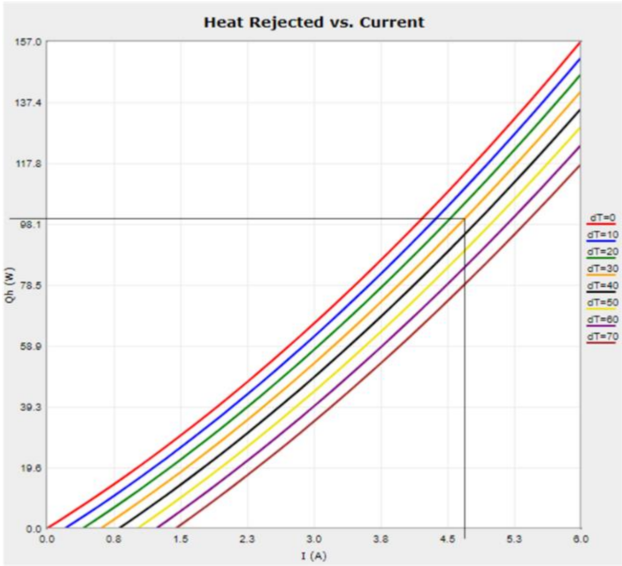


Figure 6. Heating performance and determination of ideal max current working point

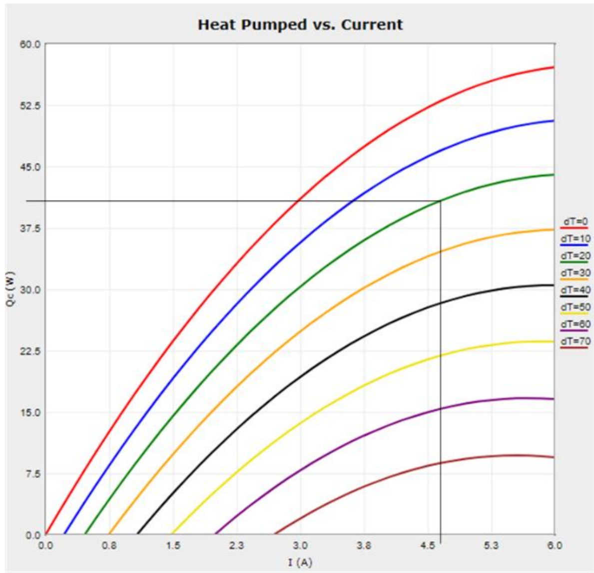


Figure 7. Cooling performance and determination of max current working point

To ensure the compatibility with common high performance CPU sinks for computers it has been necessary to limit the maximum hot side heat flux to max 100 W, which is in line with common AMD processors. It is assumed for winter cycle a $\Delta T_{max} = 30°C$. Ideal heating and cooling working ranges have been indicated in Figure 6 and 7.

Voltage graph against Current is presented in Figure 8 and is important to setup the Peltier cells behavior.

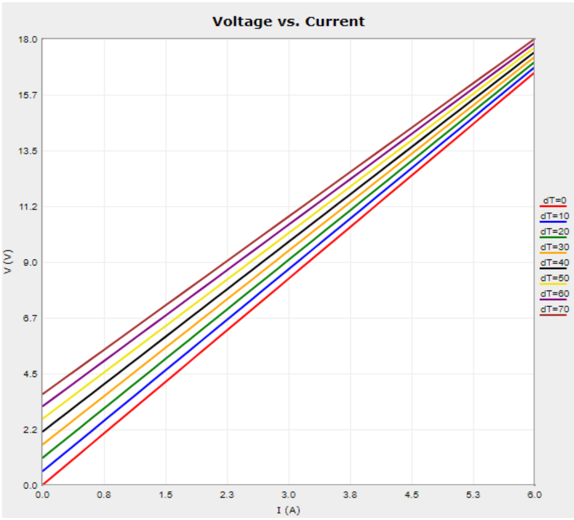


Figure 8. Voltage vs. current for the specific Peltier cell

6. HEAT EXCHANGE SYSTEM DIMENSIONING

The above assumptions allow an effective dimensioning of the Peltier cells plant and the related heat exchange system. TE modules will be used for both heating and cooling air. This will be done by heat transfer from the Peltier modules. The heat transfer to the air is transferred from the cell by the fin conduction and from the fin to the through convection.

It can be possible to evaluate heat transfer to the air:

Cold side

Heat absorbed by Peltier cells:

$$\dot{Q}_C = 2N\left(\alpha I T_C - \frac{R}{g}\frac{I^2}{2} - Kg(T_H - T_C)\right) \tag{16}$$

Heat subtracted from air by convection:

$$\dot{Q}_C = A_{exc} h_{exc,C}(T_{Cm} - T_C) \tag{17}$$

Air thermal balance:

$$\dot{Q}_C = \dot{m}_{air} C_{p,air}(T_{goal} - T_{in}) \tag{18}$$

Hot site

Heat produced by Peltier cells:

$$\dot{Q}_H = 2N\left(\alpha I T_C + \frac{R}{g}\frac{I^2}{2} - Kg(T_H - T_C)\right) \tag{19}$$

Heat transferred by convection heat exchange:

$$\dot{Q}_H = A_{exc} h_{exc,H}(T_H - T_{Hm}) \tag{20}$$

Air thermal balance:

$$\dot{Q}_H = \dot{m}_{air} C_{p,air}(T_{goal} - T_{in}) \tag{21}$$

It is also possible to evaluate he COP of both cooling and heating process:

$$COP_C = \frac{\dot{Q}_C}{I \cdot V} \tag{22}$$

$$COP_H = \frac{\dot{Q}_H}{I \cdot V} \tag{23}$$

At any temperature it is possible to evaluate the performances of the adopted Peltier cell as a function of the electric current. The performances have been evaluated at different reference temperatures for the building.

The heating performances have been simulated by CFD. Both heating and cooling situation has been simulated. A maximum heating condition is ensured in the range of 5°C.

A heat sink by cylindrical pins is assumed. Different geometries have been tested. They have been analyzed by Trancossi et al. [21] who have optimized a specific heat exchanger design, with the aim of reducing losses of pressure. The optimal configuration has been determined assuming that the heating process uses air inlet at 5°C and average exchanger temperature at 30°C. The cold side is supposed in contact with the external environment at 0°C and, consequently, ΔT is around 30°C. The same configuration has been observed optimal for cooling in which the following conditions has been assumed: air inlet temperature 28°C, exchanger temperature 20°C, the difference of the temperature is expected to be 10°C.

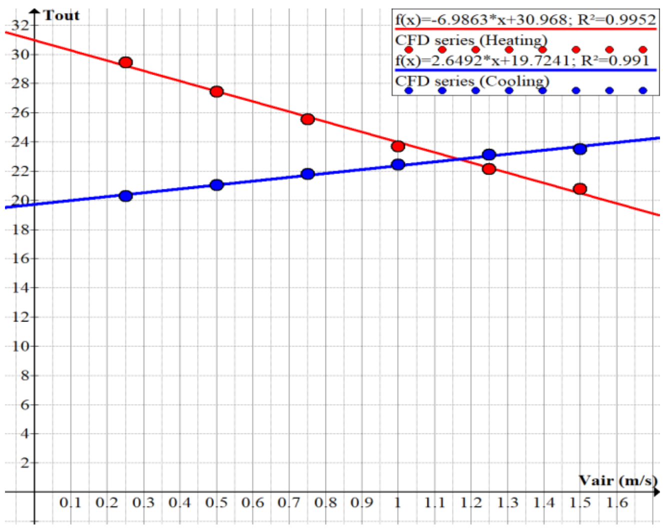


Figure 9. Sample of CFD values by Trancossi et al.

An alternative could be the adoption of any well known ventilated heat sink for CPUs.

In any case the simulation results presented in Figure 9 shows a sample of the temperature that can be achieved for different airspeeds. It has been assumed a section with equal sides of 0.06 m. in this case the volumetric airflow is 0.0036 m^3/s (1m/s). in this case the temperature jumps are pretty small. It is evident that one fixed the operative temperatures at an adequate value that ensures an adequate efficiency of the Peltier cells. If the flow rate is decreased a higher temperature will be achieved in heating mode and a lower in cooling mode. Simulations have shown that the temperature change would increase at lower speeds.

The above calculation shows clearly that the cooling system dimensioning leads the design activity, because of both much higher cooling needs and much lower cooling COP with respect to the heating process.

7. SYSTEM POWER AND ENERGY NEEDS

The energy power and average consumption of the system can be evaluated. The power has been evaluated in extreme conditions that consider both winter and summer conditions:

Heating: T_{env}=-5°C; T_{build}=20°C;

Cooling: T_{env}=36°C; T_{build}=26°C;

In this case it has been evaluated that 15 Peltier cells ensures an effective and adequate acclimatization of the reference building. In particular the installed heating power is around 850 W for cooling and 1500 W for heating.

Usually a much reduced power will be required during common conditions, also because of the important solar contribution to the heating process.

A total heat of 1015 kWh/year (with an electric need of around 376 KWh_e/year) and 2100 kWh/year during summer (with electric needs around 1100 KWh_e/year) are determined. This important characteristic of the building has a primary importance in the case its energy needs are expected to be fulfilled by renewable sources. In particular, it deals perfectly with the use of photovoltaic energy because it is much higher during summer than in winter.

8. CONCLUSIONS

This paper presents a sample of design integration of a Peltier cell based heat pump into a reference energy efficient container house. A preliminary design has been performed by assuming high efficiency and long lifecycle Peltier cells.

The plant has been defined on the basis of the much higher power needs for cooling. Energy consumption shows clearly the much higher impact of summer cooling with respect to winter heating at the latitude of Bologna (Italy).

This paper clearly demonstrates the feasibility of Peltier cells cooling in the specific case which have been considered. in addition, it also demonstrates that the power and energy balances facilitate the use of photovoltaic energy. The results are interesting and open the road to a diffused experimental activity for testing the acclimatization system on real operative conditions.

In addition an effective evaluation of comfort conditions involving both indoor air temperature and radiant effects according to Cannistraro et al. [22-23].

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NOMENCLATURE

W	Work/Energy (J)
P	Power (W)
I	Current (A)
V	Voltage (V)
R	Resistance (Ω)
Q	Heat/Energy transferred (J)
Q_C	Cold side heat transfer (J)
Q_H	Hot side heat transfer (J)
T	Temperature (K)
t	Time (s)
T_H	Hot side temperature (K)
T_C	Cold side temperature (K)
T_m	Mean temperature (K)
T_{house}	Temperature into house (K)
T_{out}	Temperature out from panel (K)
T_{in1}	Temperature in at front of panel (K)
T_{in2}	Temperature in at back of panel (K)
T_p	Temperature after passing PV cells (K)
A_{TE}	Area of thermoelectric element (m^2)
Q	Heat flux (W/m^2)
h_c	Convective heat transfer coefficient cold side - air (W/m^2*K)
h_h	Convective heat transfer coefficient hot side - air (W/m^2*K)
$C_{p, air}$	Air specific heat (J/K*kg)
m_{air}	Mass flow ventilation air (kg/s)
K	Thermal conductivity (W/m*K)
Z	Figure of merit (K)

Greek symbols

η	Carnot efficiency (%)
α	Seebeck coefficient (V/K)
π	Peltier coefficient (J/A)
ρ	Resistivity (Ω m)
ΔT	Temperature difference TH-Tc (K)