OPTIMAL PERFORMANCE OF AIR/AIR THERMOELECTRIC HEAT PUMP (THP) COUPLED TO ENERGY-EFFICIENT BUILDINGS COUPLING IN DIFFERENT CLIMATE CONDITIONS

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ABSTRACT

Temperature control systems for building tend to be more efficient. In this context, the air-to-air thermoelectric heat pump (THP) with an energy-efficient building is an interesting alternative to classic thermodynamic system. In the study, we focus on the optimal number of thermoelectric modules and the optimal electrical current for three standard cases of coupling: (i) the THP is coupled to an exhaust/supply mechanical ventilation system (ESMVS), (ii) the THP is coupled to an ESMVS and an air-to-air heat exchanger, and (iii) the THP is installed with an ESMVS and an earth-to-air heat exchanger in three different cities in France (Trappes, La Rochelle and Nice). The performance is quantified using two different COP definitions: performance of THP only (COP_{HP}) and performance of THP coupled to energy efficient building (COP_u) with seasonal conditions.

We show that for each coupling case and each climate, an optimal number of modules exists. It gives the maximum performance of the THP and can be approached for a given set of operating conditions, by simply adapting the electric current for each condition. This method allows achieving the maximum performance and reducing the materials cost compared to the classical design based on nominal conditions.

1. INTRODUCTION

The operation of thermoelectric heat pump (THP) is based on Peltier effect to product cold and hot fluxes by supplying an electrical current, which leads to pump thermal power from the cold side to the hot side [JCA. P., 1834]. THP shows many advantages compared to standards heating systems [B.J. Huang et al., 2000]: no moving parts, low maintenance cost and high reliability. According to Rowe [Rowe D. M.,1995] the THP is competitive in terms of performance when the temperature difference between sources of the thermoelectric module (TEM) is minimized as it could be in a building [X. Xu et al., 2007] and especially for an efficient building.

Recently, Cosnier et al. [M.Cosnier 2008] and Li [Li, T., et al 2009] studied a system that cools or warms airflow in a building by means of thermoelectric modules. Experimental results showed that a COP_{HP} higher than 1.5 can be reached in an air-cooling mode with a low temperature difference (5–10°C). The heating COP_{HP} reported in Li et al. [Li, T., et al 2009] is over 2.5 with a THP associated with an exhaust/supply mechanical ventilation system and a stable outside temperature (6–8°C).

The goal of this study was to determine the optimal design and operating conditions of an air-to-air THP coupled to energy-efficient buildings with a mechanical ventilation system. Particular attention has to be paid to the definition of the COP, quantifying the THP performance, which can be defined in different ways. We consider and compare the following definitions: COP_{HP} as it relates to the THP and COP_u as it relates to the useful energy transferred to the building. These two definitions lead to different values as the air loop is opened to the ambient surrounding.

We consider three cases of coupling with different heat recovery systems with an exhaust/supply mechanical ventilation system (ESMVS) and three different French geographies with (from coldest to hottest climate): Trappes, La Rochelle and Nice. The number of modules and the corresponding optimal electrical current are optimized to meet the power required in the building in relation to the outside temperature, in order to maximize the COP.

These performances are also compared to those obtained considering the classical design method, based on instantaneous nominal conditions.

2. SYSTEM

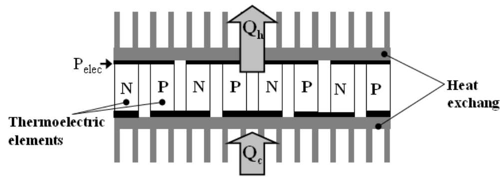

Figure 1 Schema of the thermoelectric element coupled to heat exchanger.

The system studied in this work is composed of a THP, made up of thermoelectric modules, coupled to heat exchangers, as shown in Figure 1. The THP provides heating/cooling fluxes and is coupled to an energy efficient building.

2.1 Thermoelectric Heat Pump (THP)

- Modelling the thermoelectric elements

The operation of a thermoelectric element (TE), with n pairs of thermoelectric legs, is described in a standard simple method that implies Peltier and Joule effects and thermal conduction. The fluxes absorbed (Q_c) and dissipated (Q_h) by a TE are written according to equations (1) and (2) [Rowe D. M.1995].

$$Q_c=2n\cdot(\alpha\cdot I\cdot T_c-0.5\cdot R\cdot I^2-K\cdot\Delta T) \quad (1)$$

$$Q_h=2n\cdot(\alpha\cdot I\cdot T_h+0.5\cdot R\cdot I^2-K\cdot\Delta T) \quad (2)$$

The parameters α, R, and K are, respectively, the Seebeck coefficient, the electrical resistance, and the thermal conductance of the TE legs at the mean temperature, with T_h and T_c the temperatures of the thermoelectric junction on the hot and cold sides respectively.

The electrical power P_{elec} is the difference between these two heat fluxes:

$$P_{elec}=Q_h-Q_c=2n\cdot(\alpha\cdot I\cdot\Delta T+ R\cdot I^2) \quad (3)$$

The analytical expression of the TE material characteristic Bi_2Te_3 [G.Fraisse2010], and the geometry of the module (ref. 9501/242/160 B, Ferrotec) [Ferrotec] are provided in Table 1 for a TEM.

DESCRIPTION	**VALUE**
Dimension of Peltier module	55×55×3.45 (mm^3)
Number of pairs of legs	242 (-)
Electrical resistivity of a leg	$(5112+163.4\cdot Tm+0.6279\cdot Tm^2)\cdot 10^{-10}$ ($\Omega.m$)
Seebeck coefficient	$(22{,}224+930.6\cdot Tm-0.9905\cdot Tm^2)$ 10^{-9} ($V.K^{-1}$)
Thermal conductivity of a leg	$(62{,}605-277.7\cdot Tm+0.4131\cdot Tm^2)\cdot 10^{-4}$ ($W.m^{-1}.K^{-1}$)

Table 1. Characteristics of the TEM

The fluid flow in the heat exchangers also results in pressure drop that must be countered by circulation auxiliary. We thus define the COP of the THP as follows.

$$COP_{HP}=\frac{Q_h}{P_{elec}+P_{fan}} \quad (4)$$

Consumption of electrical circulation auxiliary P_{fan} is included in these calculations, with P_{fan} set to 0.1 ($W.h.m^{-3}$) in this study for each fan. The value of P_{fan} depends on the house volume. The value of P_{fan} corresponds to the high-performance value given by the ESMVS manufacturer.

Figure 2 plots the variation of COP_{HP} depending on the number of modules in the THP and the temperature difference ΔT between the hot and cold sides of the module. The electrical current is adapted to reach a load of Q_h=1000 W.

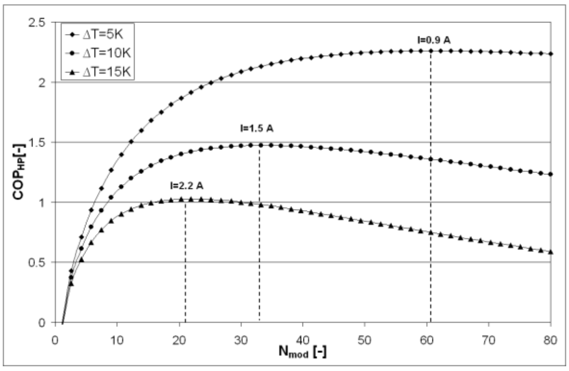

Figure 2. COP_{HP} (depending on N_{mod} and temperature difference, with T_h=293 K, Q_h=1000 W)

As shown in Figure 2, for any temperature difference, a number of thermoelectric modules exists (N_{mod}), leading to the maximal COP_{HP} for a given hot power Q_h and a given P_{fan}. As expected, the maximal COP value decreases as the temperature difference ΔT increases. The optimal number of modules N_{mod}^{opt} also decreases as the ΔT increases. That is, the optimal number of modules N_{mod}^{opt} and the corresponding optimal COP_{HP} are mainly set by the temperature difference ΔT and the load Q_h.

- Coupling to the heat exchangers

The heat sinks, coupled on each side of the thermoelectric modules to transfer heat from the sources to the THP, constitute the second element of the THP. These heat sinks are designed to reduce the temperature difference, for each source, between the mean temperature of the source and the temperature of the thermoelectric heat sinks of the hot and cold sides, i.e., it reduces the thermal resistance of the heat sinks. In our study, thermal resistance R_{th} is set to 0.001 [K/W] according to simulation results of an impinging jet heat exchanger [S. V. Garimella, 2000].

2.2 Coupling THP to a building

The reference building used in this work is an efficient-energy building named INCAS house located in the site of INES (L'Institut National de l'Energie Solaire) at Bourget-du-Lac. The surface of the building considered is S_b 97.5 m^2 and it has a height of 2.7 m (two floors). The different THP coupling cases are presented in this section.

2.2.1 Configurations

The different THP coupling cases are shown in Figure 3, 4 and 5. Note that in all the cases studied here, the outside fresh air flow rate τ_{fresh} is set to 0.5 ACH (this level allows sufficient air renewal for health considerations). Then fresh air flow τ_{fresh} and recycled air flow τ_{rec} are mixed. The total supply flow rate τ_s is set at 3 ACH (780 $m^3.h^{-1}$).

- Case 1: ESMVS

The detailed information of the coupling between a THP and a building for case 1 is shown in Figure 3.
On the hot side, the fresh air of the THP is taken directly from the outside of the building before mixing with recycled air. On the cold side, the exhaust air is mixed with a flow of outside air, ensuring balanced flows on both sides of the THP.

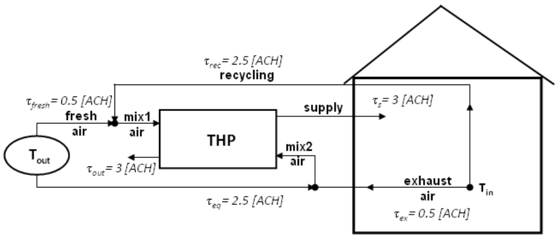

Figure 3 Schema of the THP associated with an ESMVS with no recycling of exhaust air at the cold side.

- Case 2: ESMVS with air-to-air heat exchanger

The second case is associated with an ESMVS coupled to an air-to-air heat exchanger. On the hot side, the fresh air of the THP is preheated by recovering heat from the exhaust air (Figure 4). The recycled air and preheated air are subsequently mixed. This results in an increase in the mixing temperature T_{mix1} at the inlet of the THP. On the cold side of the THP, the flow of outside air is adjusted to balance the flow rates on both sides of the THP. In our study, the efficiency of the heat exchanger, η, is set to 0.7.

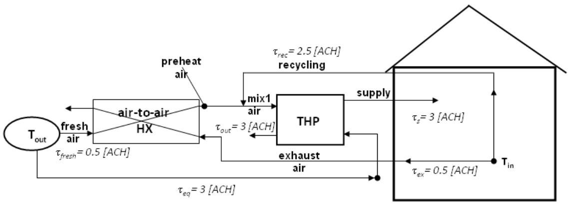

Figure 4 Schema of the THP is associated with an ESMVS coupled to an air-to-air heat exchanger.

- Case 3: ESMVS with earth-to-air heat exchanger

The last case is associated with an ESMVS coupled to an earth-to-air heat exchanger. The fresh air of the THP is taken directly from outside the house, as in the first case. However, if the outside temperature T_{out} is less than 10°C, air flows through the earth-to-air heat exchanger to reach a constant temperature of +10°C. If the outside temperature is warmer than 10°C, air is taken directly from outside (earth-to-air heat exchanger non active).

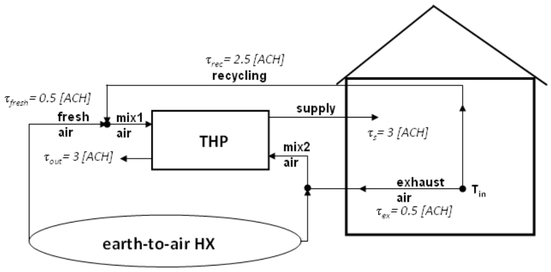

Figure 5 Schema of the THP is associated with an ESMVS coupled to an earth-to-air heat exchanger.

We considered the inside temperature is set to 19°C.

- Climates

The system “THP+INCAS house” is placed in three cities in France corresponding to three distinct climates. These cities are: Trappes (zone H1), La Rochelle (zone H2) and Nice (zone H3). H3 is the area where the climate is warmer, that is to say, the heating requirement is lower.

2.2.2 COP assessment

The goal of this study is to obtain the best seasonal performance of a THP to heat a building for the heating period. Performance is quantified using the COP, which can be defined in different ways:

- The $COP_{HP}{}^s$ takes into account the hot power of the THP, normalized by the total power consumed by the system, including the consumption of the auxiliary circulation fan, P_{fan}.
- The $COP_u{}^s$ takes into account the power supplied to the building Q_u, normalized by the total electrical power consumed by the thermoelectric modules and the fans.
- The COP_n is relative to the THP only with the nominal operating conditions defined in the European standard NF EN 14511 [NF EN 14511]

These COP are respectively described by the equations (5), (6) and (7), are:

$$COP_{HP}^{s} = \frac{\Sigma Q_h(i)}{\sum_i (P_{elec}(i) + P_{fan}(i))} \tag{5}$$

$$COP_{u}^{s} = \frac{\Sigma Q_u(i)}{\sum_i (P_{elec}(i) + P_{fan}(i))} \tag{6}$$

$$COP_n = \frac{Q_h}{P_{elec} + P_{fan}} \tag{7}$$

2.2.3Modeling

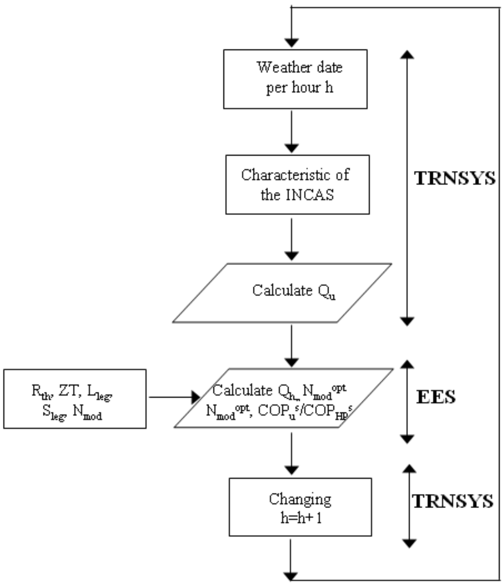

Figure 6 Modeling algorithm of the coupling THP in INCAS

The different coupling cases are calculated with the softwares EES and TRNSYS. TRNSYS sets specific heating needs of the building Q_u of INCAS house, depending on weather conditions in which it is placed. We assume that the thermal resistances, figure of merit, properties, and dimensions of the thermoelectric legs are also known and fixed (table1). Outside temperature, heating power of the building, are used for data input to the model EES. Then, we seek the optimal number of modules and the corresponding electrical current needed for the heating requirement of building Q_h.

3. RESULTS

3.1. Nominal COP

The performances of the different coupling cases have to be compared to those deduced for the nominal operating conditions defined in the European standard NF EN 14511, as reference. Thermoelectric properties, the air flow considered (790m^3/h) and thermal resistances are kept unchanged. For the THP considered, calculations gives $N_{mod}^{n}=51$, and $COP_n=1.7$. As the COP_n is relative to the THP only, this value and its corresponding optimal number of modules is independent of the coupling considered, and thus constant for cases 1 to 3.

3.2. Coupling influence with optimal number of module

We compare seasonal performances regarding to different methods to design a THP. The seasonal performance for the three different weather conditions is considered.

This study introduces both seasonal coefficient of performance COP^s_{HP} and COP^s_u to take into account outside temperature variation during the cold season. Note that the optimal number of modules leading to maximize COP_{HP} is the same when maximizing COP_u. Actually, the optimal number of modules N_{mod}^{opt} is the one always leading to a minimized electrical power P_{elec}. Besides, Q_h and Q_u both vary linearly with the outside temperature. Therefore N_{mod}^{opt} is the same for $COP^s_{HP}{}^{opt}$ as for $COP^s_u{}^{opt}$.

To compare the performance degradation compared to the ideal case where the number of modules can be adapted for each temperature condition, we estimate the performance gap (*PG*) between COP^s_{HP} for a fixed number of modules and $COP^s_{HP}{}^{opt}$ obtained for a variable optimal number of modules depending on the outside temperature.

$$PG(\%) = \frac{COP^s_{HP}(N_{\mathrm{mod}}) - COP^s_{HP}(N^{opt}_{\mathrm{mod}}(T_{out}))}{COP^s_{HP}(N^{opt}_{\mathrm{mod}}(T_{out}))} \qquad (8)$$

The following figure plots the *PG* between COP^s_{HP} and $COP^s_{HP}{}^{opt}$ for the different cases.

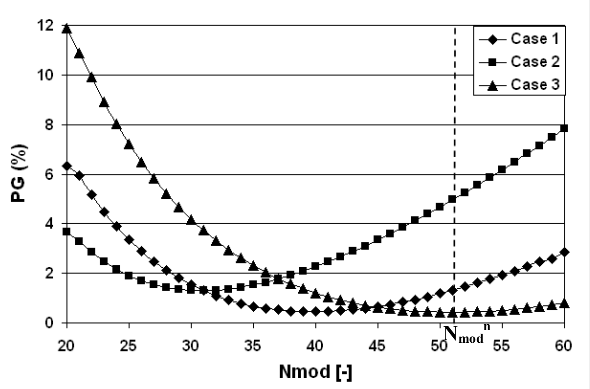

Figure 7 COP^s_{HP} and $COP^s_{HP}{}^{opt}$ performance gap in the city of Trappes according to the different coupling cases.

These *PG* values make it possible to find the optimal number of modules according to seasonal performances of the THP coupled to the building. The optimal number of modules is deduced when the PG is minimal, that is to say, when the performances are the closest to the ideal case, with a number of modules varying with the outside temperature. Figure7 shows that the optimal numbers of modules are 40, 30, and 50 for cases 1, 2, and 3, respectively. The low values of PG reported means that the seasonal performance degradations are low when selecting the appropriate number of modules. We also note that each coupling needs different number of modules. There are two reasons for different number of module. First, there is an influence of Q_h varying with the different cases considered (in this case Q_h has small variations). Secondly, the temperature difference between the two sides of the thermoelectric system affects the optimal number of modules, as shown in Figure 2. When ΔT increases, the optimal electrical current also increases, thus resulting in a decrease of the optimal number of modules. Therefore, case 2 requires fewer modules. That means that the sizing of the THP cannot be deduced easily from the nominal conditions.

The performance gap resulting in a sizing based on nominal conditions is also shown in Figure 7 (for N_{mod}=51), for any coupling case.

We compare the seasonal COP for the heat pump obtained with three different sizing methods: N_{mod} in ideal case (N_{mod} is variable for each T_{out}), N_{mod}^{opt} determined with our method (N_{mod}^{opt} is determined for each case with figure 7) and nominal N_{mod}^{n} (according to the nominal conditions). Variations on the number of modules for the different design approach are calculated as follow:

$$\Delta N_{\text{mod}}\,(\%) = \frac{N_{\text{mod}} - N^{n}_{\text{mod}}}{N^{n}_{\text{mod}}} \qquad (9)$$

According to the results, our design method leads to values of COP^{s}_{HP} close to those obtained from the ideal case N_{mod}. The maximum PG is 1.3% in case 2.

We also show that there is a slight difference between the ideal case and the nominal case for COP^{s}_{HP}. The performances could be improved by 1.1% for case 1, 5.2% for case 2 and 0.5% for case 3 if the number of modules is optimized. Beside, this optimization also leads to a large reduction of the module quantity by -21% for case 1, -41% for case 2 and -2% for case 3 compared to nominal conditions.

3.3. Influence of the climate with optimal number of module

Figure 8 shows performance gap for different climates (city of Trappes, La Rochelle and Nice) with coupling case 1. Even if climate between these three cities is slightly different, PG is similar whatever the number of module. Moreover, the optimal number of modules is the same for the three cities.

The power needed Q_h and ΔT are small when the climate is warm like in Nice. When Qh is small, we need less N_{mod}. Furthermore, when ΔT is small, we need more N_{mod}. Finally, we need the same range of optimal number of module for the three cities. So we can conclude that, the optimal number of modules is more influenced by the coupling cases.

We also show that the performance gap is slightly the same (0.5%) for cases 1, 2 and 3. In addition, we can see that the performance could be improved by 1.3%. The module quantity is also largely reduced by -21% for the three studied cities of Trappes, La Rochelle and Nice compared to nominal conditions.

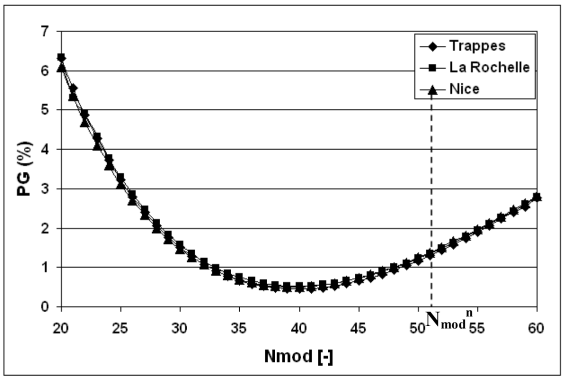

Figure 8 COP^{s}_{HP} and $COP^{s\ opt}_{HP}$ performance gap in case 1 for the different cities.

3.4. Influence of COP

With the optimal number of modules for each coupling and different climates, we obtain the COP^{s}_{HP} and COP^{s}_{u} for winter season.

Figure 9 compares the COP^{s}_{HP} with the optimal number of modules. We note that THP is the most efficient for Nice, the hottest climate. When outside temperature is high, the temperature difference between cold and hot side of THP is low, resulting in a high performance of THP. The coupling case 3, with earth-to-air heat exchanger, help to reduce the difference temperature on both sides of the module THP when the outside temperature is lower than 10°C (earth-to-air heat exchanger active), and this difference is to equal those of case 1, when the outside temperature is higher than 10°C (earth-to-air heat exchanger non active).

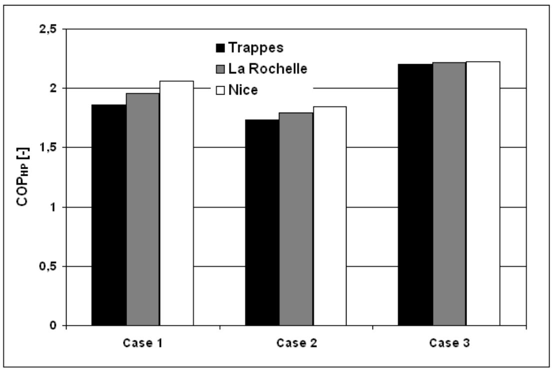

Figure 9 Comparison of COP_{HP} for different climates and the three coupling cases

Besides, case 2 is less efficient than case 1, because the exhaust air flow is mixed with fresh air on the cold side in case 1, whereas the exhaust air is used to preheat the fresh air of the hot side and fresh air is directly used for the cold side in case 2. The cold side no longer receives benefits from heat gain provided by the exhaust air in case 2. For this reason, the temperature difference between the two sides of the TEM becomes higher than that of case 1. Therefore, COP^{s}_{HP} decreases in case 2 compared to case 1.

So, considering COP^s_{HP}, the city of Nice with coupling case 3 shows the best performance with COP_{HP} up to 2.2.

Similarly, we evaluated COP^s_u which takes into account the power supplied to the building Q_u. Figure 10 shows that the tendencies deduce from COP^s_{HP} are different. The COP^s_u is much smaller than $COP^s_{HP.}$ This is because the reference system is different. Here, Q_u takes into account 0.5 ACH of fresh air so it is lower than Q_h. In Nice, case 3 shows poor performance compared with case 1 and 2 due to the consumption of air supply system P_{fan}. Actually, P_{fan} is a fixed value whatever the climate, so when the outside temperature is high, the value of P_{fan} is overestimated, resulting in a decrease of the system performance COP^s_u.

Figure 10 Comparison of COP_u for different climates and the three coupling cases

The coupling to an air-to-earth or air-to-air exhanger allows to reduce THP consumption part, leading to improve COP_u for coupling case 2 and 3.

In best conditions, a COP_u of 1.7 can be reached with the coupling 3 at Trappes.

CONCLUSION

The goal of this study was to determine the optimal number of thermoelectric modules and the optimal electrical current of a THP coupled to an energy-efficient building. Three selected cases of coupling with different heat recovery systems are considered: an air-to-air heat exchanger, an earth-to-air heat exchanger, and no additional heat exchanger associated with an exhaust/supply mechanical ventilation system (ESMVS). These coupling cases are also studied for different French cities.

It has been shown that for all cases, an optimal number of modules exists to approach the seasonal optimal COP_{HP}/COP_u, regardless of the operating conditions, by simply adapting the electrical current. The optimal number of modules is unchanged regarding the COP_{HP} or the COP_u. Indeed, the optimal number of modules is driven by Q_h and the ΔT between both sides of the TEM, which affects the optimal electrical current. This optimal number of modules corresponds to the minimum electrical power consumption required to meet the demand Q_h.
The number of modules with our design method (case1: 30, case2: 40 and case 3: 50) leads to values of seasonal COP^s_{HP} close to those obtained from the ideal case N_{mod}. The method we suggest in this paper is a pertinent way to estimate the optimal number of modules (decrease the thermoelectric material cost up to 41%) and improve the system performances (increased by 5.2 % maximum in case 2) depending on the different coupling and building considered compared to nominal condition (N^n_{mod}=51).
It is important to correctly define a reference system as we have shown that differences in climate conditions can lead to very different results between COP_{HP} and COP_u.
If COP_{HP} is the best for hottest climate, it is the sometimes opposite for COP_u, depending on the sizing of the consumption of air supply system with Q_u.
With our method, we can achieve the maximum performance : sesonal COP_{HP} reaches 2.2 in case 3 at Nice and sesonal COP_u reaches 1.7 in case 3 at Trappes.

NOMENCLATURE

Symbols

ACH= Air change per hour, *Vol/h*
COP= coefficient of performance
$C_{p=}$ specific heat capacity, $J.Kg^{-1}K^{-1}$
I= electric current, A
K= thermal conductance, $W.K^{-1}$
$\dot{m}$ = mass flow, $kg.s^{-1}$
N_{mod}= number of modules
P_{elec}= electrical power,W
Q = heat flux,W
$R_{th=}$ thermal resistance, $K.W^{1}$
T= temperature, K
ΔT= temperature difference $(T_h - T_c)$,K
Z= figure of merit, K^{1}

Greek Symbols

a= Seebeck coefficient, $V.K^{-1}$
λ= thermal conductivity, $W.m^{-1}.K^{-1}$
ρ= electrical resistivity; $\Omega.m$
τ= Thomson coefficient, $V.K^{-1}$

Subscripts

c = cold side of the junction
h= hot side of the junction
m= average from inlet to the outlet of the hot and cold sides of the TEM
max = maximum
min= minimum

n= nominal
opt= optimum
u = useful performance in the building

ACKNOWLEDGEMENT

The authors extend their thanks to EDF for supporting the present work.

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