Dynamic exergy analysis of an air source heat pump

A. Angelotti, P. Caputo, G. Solaini
Building and Environment Science and Technologies (BEST) Department
Politecnico of Milano
v. Bonardi 3, 20133 Milano, Italy
e-mail: adriana.angelotti@polimi.it, paola.caputo@polimi.it, giulio.solaini@polimi.it

Abstract

Exergy flows related to heating and cooling in buildings are very sensitive to the choice of the reference state, since climatisation systems operate very close to the dead state. Some authors recently proposed to adopt the time dependent outdoor conditions as reference state. Since dynamic exergy calculations would be more time consuming than steady state, comparing the results of the two approaches could help identifying the cases when the dynamic methodology should be preferred. Therefore in this paper the yearly behaviour of a reversible air source heat pump (ASHP) providing heating, cooling and dehumidification to a simple building was simulated by means of a dynamic energy simulation software (TRNSYS), taking into account different climates. At every time step, the exergy of the delivered and consumed energy was calculated. Moreover the instantaneous, the monthly and the seasonal exergy efficiency of the ASHP were obtained. Dynamic exergy efficiencies were finally compared with the steady state values and some useful considerations regarding the differences were carried out.

Introduction

Exergy analysis is an important methodological tool, whose employment may allow designers to improve and optimize systems and processes. A detailed calculation of exergy flows can be achieved by setting up energy, entropy and exergy balance equations, as in [1], after having defined a suitable reference temperature. In general the choice of the reference temperature is of capital importance in exergy analysis. However, when the energy conversion system operates far from the reference environment, the corresponding exergy flows are not very sensitive to the its definition. This typically happens in the case of power plants. In turn, space climatisation systems operating conditions are usually close to the reference conditions and therefore their exergy performance is largely influenced by the choice of the reference environment. Anyhow presently a convention for the selection of the reference temperature for this kind of applications is still lacking [2]. Most authors adopt a constant temperature, but follow different approaches, choosing either a seasonal or annual mean value or a design value. In turn some authors suggest a time dependent outdoor temperature [3, 4], leading to perform dynamic exergy analyses. Since a dynamic exergy analysis would obviously be more time consuming than a steady state one, a comparison between the results of both approaches is performed in [5] and [6]. Sakulpipatsin et al. [5] calculate the exergy of indoor air in buildings and show that in a cold climate a steady temperature corresponding to the annual mode value of the outdoor temperature may be an acceptable reference state. In turn for a hot and humid climate they point out the importance of considering also the humidity content of the outdoor air, and show that steady state calculations lead to great differences compared to dynamic ones. Angelotti and Caputo [6] calculate both steadily and dynamically the exergy efficiency of some climatisation systems in two representative Italian climates. They show that steady state evaluations based on design temperatures may be significantly different from dynamic ones, especially for cooling system and for a warm climate. They show however that a steady state calculation based on a monthly mean temperature may lead to small differences with respect to the dynamic. These results show that further investigations are necessary to understand when a dynamic exergy analysis would be mandatory. Therefore, the present study aims at investigating further the differences between steady and dynamic evaluations of the exergy performances of HVAC systems, starting from the previous analyses by the same authors [6] and providing a more comprehensive dynamic evaluation. This research focuses on the behaviour of an air source heat pump (ASHP), chosen as a system whose energy performance is strongly affected by the outdoor air conditions. While in [6] the dynamic was treated in a simplified way, by assuming at every time a perfect matching between the building demand and the system supply, in this study the real coupling between the system and the building, as well as the action of the system control, are considered through a detailed annual simulation.

Methodology

Main aim of this work is to highlight in which climatic contests the dynamic simulations should be strongly recommended instead of the steady ones in order to give a correct evaluation of the exergy performances. In particular, the Italian context and two climatic conditions (Milano in the North and Palermo in the South) are considered. Moreover, the research aims at investigating if it is possible to define a steady state methodology whose results would have a limited discrepancy with respect to the dynamic one. Therefore a dynamic evaluation of the exergy efficiency of an ASHP providing heating and cooling to a residential building located alternatively in the two climates is carried out. The analysis is based on the results of a dynamic simulation performed with the well known software TRNSYS [7]. Subsequently, three steady state calculations of the exergy efficiency of the same system are proposed, starting from the simplest to the more detailed:

- a steady state analysis adopting design temperatures given by the Italian standards as reference temperatures T_0;
- a steady state analysis adopting monthly mean temperatures given by the Italian standards as T_0;
- a steady state analysis adopting monthly mean temperatures taken from the typical meteorological year data set used for the dynamic simulations as T_0.

Finally the results of the dynamic and the steady analyses are compared and discussed.

Exergy efficiency

In order to evaluate the exergy performance of the ASHP, an exergy efficiency is defined as follows:

$$\psi = \frac{\dot{E}x_U}{\dot{E}x_S} \tag{1}$$

where $\dot{E}x_U$ represents the exergy rate of the delivered heat/cold and $\dot{E}x_S$ the exergy rate spent by the ASHP. Therefore $\dot{E}x_U$ may be evaluated as:

$$\dot{E}x_U = \sum_{j=1}^{N} \dot{E}x_{U,j} = \sum_{j=1}^{N} \dot{Q}_{U,j}\left(1-\frac{T_0}{T_j}\right), \tag{2}$$

where T_0 is the reference temperature and N is the number of thermal zones in the building, each having an indoor temperature T_j and a delivered heating or cooling rate $\dot{Q}_{U,j}$. The exergy spent by the ASHP, assuming the boundary of the analysis at the building and system level, is simply given by the electricity consumption rate i.e. $\dot{E}x_S = \dot{W}$. If a dynamic calculation is carried out, the exergy efficiency ψ may be evaluated at every time step t_k. Therefore (Eq. 1) becomes:

$$\psi(t_k) = \frac{\sum_{j=1}^{N} \dot{Q}_{U,j}(t_k)\left(1-\frac{T_0(t_k)}{T_j(t_k)}\right)}{\dot{W}(t_k)} \tag{3}$$

and a monthly or seasonal mean exergy efficiency ψ_{dyn} may then be calculated as an average value:

$$\psi_{dyn} = <\psi(t_k)> = \frac{1}{m}\sum_{k=1}^{m}\psi(t_k). \tag{4}$$

In turn in a steady state calculation T_0 is set to a constant value, the indoor temperatures are all assumed equal to the desired indoor temperature T_i and the energy rates are given according to the set T_0. Then (Eq. 1) becomes:

$$\psi_{stea} = \frac{\dot{Q}_U}{\dot{W}}\left(1-\frac{T_0}{T_i}\right) = COP(T_0)\left(1-\frac{T_0}{T_i}\right) \tag{5}$$

(Eq. 5) shows that ψ_{stea} may be expressed in terms of the ASHP coefficient of performance (*COP*) and of the Carnot factor of the delivered heat or cold energy.

Definition of the seasons

The heating season is defined by law in Italy: for Milano it ranges from October 15th and April 15th, while for Palermo from December 1st to March 31st. The cooling season is not yet defined by law in Italy; in this work it is simply considered as the complementary period of the year with respect to the heating season. It may be observed that, within the above defined seasons, hours with no heating or no cooling demand could happen; these cases are properly predicted in a dynamic simulation.

Dynamic analysis

Adopting Meteonorm weather files, comprising an annual set of hourly values of climatic data, a TRNSYS 16.01 dynamic simulation of the behaviour of an ASHP coupled to a typical residential unit of about 100 m^2 is performed. The building is divided in three thermal zones (utilities faced North, living faced South and night faced East and West). Internal gains and occupational schedules are compatible with the destination of the building. The envelope characteristics (U values and inertia) differ in Milano and in Palermo according to the Italian national regulation. The building heating and cooling sensible energy figures are then:

- in Milano: heating demand: 41 kWh/m^2; cooling demand: 7 kWh/m^2; heating peak load: 4,4 kW; cooling peak load: 2,3 kW;
- in Palermo: heating demand: 5 kWh/m^2; cooling demand: 17 kWh/m^2; heating peak load: 2,5 kW; cooling peak load 3,0 kW.

The ASHP is modelled through the non standard component type 655 from the TESS library. The characteristics of the ASHP are taken from an example file provided by the same library. The heating and cooling COPs are plotted in Fig. 1 towards the outdoor temperature. Since different peak loads are found in the two sites, the ASHP size is scaled accordingly. In both sites during winter the ASHP should maintain 20°C during the day and 16°C during the night, while in summer an intermittent regime is assumed, with a set point temperature of 26°C during the day. The indoor temperatures of the three thermal zones T_j, the provided heat or cold rate $\dot{Q}_{U,j}$ and the electricity consumption rate $\dot{W}$ are then calculated for every time step. Monthly mean and seasonal dynamic exergy efficiencies ψ_{dyn} are calculated according to (Eq. 4).

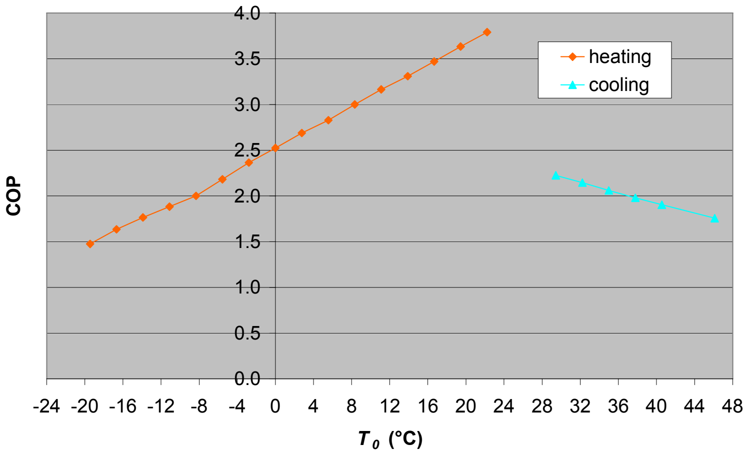

Fig 1. COP versus outdoor temperature T_0 of the ASHP (taken from the example data for the type 655)

Steady state analyses

As already mentioned, three kinds of steady state evaluations are proposed.

In the simplest approach, the reference temperature T_0 is set equal to the design temperature typically used in Italy to size HVAC systems, named here $T_{0,design}$, and indoor temperatures are set at design conditions according to Italian standards. The exergy efficiency of the ASHP $\psi_{stea,design}$ is calculated as in (Eq. 5), where $COP_{stea,design} = COP(T_{0,design})$ according to the curves plotted in Fig. 1. The reference data and the corresponding results are reported in Table 1. Since design temperatures are usually extreme temperatures happening with a low frequency, and the ASHP is expected to operate also in less extreme conditions, a second steady state approach is then considered, with reference temperatures corresponding to the monthly mean values given by the Italian standards. Reference data adopted in this case and the corresponding results are reported in Table 2 for Milano and Table 4 for Palermo. In principle both monthly and seasonal exergy efficiencies, named $\psi_{stea,mean}$, may be

calculated through (Eq. 5). However it should be remarked that, since in both climates the mean outdoor temperature in the cooling months is below the indoor design temperature (26°C), no exergy efficiency can be evaluated for the cooling period.
Monthly mean temperatures given by national standards are easily available for a steady state evaluation, but, in general, differ from the monthly mean values that may be calculated from any weather file to be used in a dynamic simulation. Therefore the comparison between the results of the steady and the dynamic evaluation might be distorted by this difference. Then a third steady state analysis is considered, where the reference temperatures are the monthly mean outdoor temperatures calculated from the Meteonorm weather file. The reference data and the corresponding results are reported in Table 3 for Milano and Table 4 for Palermo. Also in this case, for the same reason, steady state evaluations in summer are not possible.

Results and discussion

Tables 1, 2, 3 and 4 report the comparison between the results of the dynamic approach and those of the different steady state. The discrepancy between the approaches is evaluated through the relative difference of the results, calculated taking the dynamic results as references. Beside the exergy efficiency figures, the tables report also the COP and the Carnot factor figures, since according to (Eq. 4) and (Eq. 5) they influence the exergy efficiency. Looking at the tables a general remark can be made: exergy performance results differ from energy performance results, because of the dependency from the Carnot factor. Quite often the discrepancy in the COP and in the Carnot factor have opposite sign and in the end the sign in the discrepancy in the exergy efficiency is determined by the Carnot factor. Then, at least for this kind of system, the dynamic effects of the Carnot factor dominate those of the COP.

	Milano		**Palermo**	
	Heating	**Cooling**	**Heating**	**Cooling**
$T_{0,design}$ (°C)	-5	32	5	32
$COP_{stea,design}$	2.25	2.15	2.81	2.15
COP_{dyn}	2.71	2.82	3.17	2.89
Relative difference	**17 %**	**24 %**	**11 %**	**26 %**
$1- T_{0,design}/T_{i,design}$	0.081	0.020	0.047	0.020
$<1-T_0(t)/T_i(t)>$	0.059	0.007	0.033	0.006
Relative difference	**-37 %**	**-202 %**	**-40 %**	**-256 %**
$\psi_{stea,design}$	0.182	0.043	0.132	0.043
ψ_{dyn}	0.157	0.017	0.100	0.014
Relative difference	**-16 %**	**-152 %**	**-31 %**	**-217 %**

Table 1. Steady state evaluation based on design temperatures compared with dynamic evaluation

Considering the comparison between steady state evaluation based on design conditions and the dynamic one (Table 1) we may notice that the differences regarding the summer period are more important than in the winter period for both sites. The cooling season relative differences could hardly be considered acceptable. Actually the relevant role played by the dynamics during the cooling season may be better understood by looking at Fig. 2, where the monthly values of ψ_{dyn} are shown with a tolerance bar given by the mean standard deviation, calculated from the set of values of the $\psi(t_k)$ (Eq. 4). Fig. 2 shows how large is the range of values covered by ψ_{dyn} during the cooling season. This result may be due to the small difference $(T_i - T_0)$, leading to a great sensitivity of the Carnot factor to the variations of T_0.

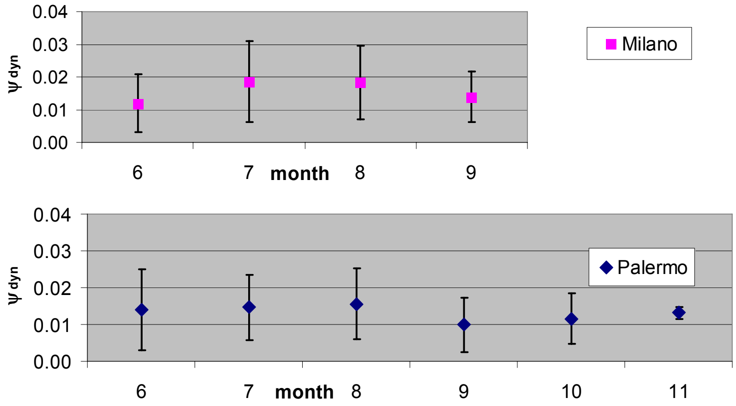

Fig 2. Dynamic exergy efficiency values in Milano (above) and Palermo (below)

Regarding the heating season, Table 1 shows that the relative difference is larger in absolute value in the warmer climate (Palermo) than in the colder (Milano). Looking at the relative differences between steady state evaluation based on mean temperatures and dynamic evaluation, reported in Tables 2, 3 and 4, we may notice that they have the same order of magnitude as in Table 1. Therefore, adopting mean values instead of design values for T_0 does not lead to significant improvements.

Month	**1**	**2**	**3**	**4**	**10**	**11**	**12**	**Heating season**
$<T_0>$ (°C)	1.7	4.2	9.2	14.0	14.0	7.9	3.1	5.7
$COP_{stea,mean}$	2.62	2.76	3.05	3.32	3.32	2.97	2.70	2.9
COP_{dyn}	2.65	2.68	2.79	2.91	2.73	2.82	2.68	2.7
Rel. difference	**-1 %**	**3 %**	**9 %**	**12 %**	**18 %**	**5 %**	**1 %**	**5 %**
$1-<T_0>/T_i$	0.058	0.050	0.032	0.016	0.016	0.037	0.053	0.044
$<1-T_0(t)/T_i(t)>$	0.062	0.061	0.055	0.047	0.058	0.053	0.061	0.059
Rel. difference	**-7 %**	**-23 %**	**-70 %**	**-195 %**	**-262 %**	**-43 %**	**-14 %**	**-34 %**
$\psi_{stea,mean}$	0.153	0.137	0.099	0.053	0.053	0.110	0.144	0.126
ψ_{dyn}	0.162	0.160	0.149	0.136	0.157	0.145	0.159	0.157
Rel. difference	**-7 %**	**-17 %**	**-50 %**	**-156 %**	**-197 %**	**-32 %**	**-11 %**	**-24 %**

Table 2. Comparison between steady state evaluation based on monthly mean temperatures from standard and dynamic evaluation for Milano

In turn on a monthly basis we may notice that the relative differences vary significantly. This result is explained by Fig. 3, showing the monthly relative difference in the exergy efficiency against the fraction of the time in a month in which the ASHP is on. The less the ASHP is on, the larger the relative difference, since the ASHP operates mostly under extreme outdoor temperatures, and then monthly mean temperatures are little representative of the real operating conditions. Fig. 3 explains also the results achieved in [6], regarding the small discrepancy between the steady state evaluation based on monthly mean values and the dynamic, since those analyses were restricted to January and July, when the system is on most of the time.

Month	**1**	**2**	**3**	**4**	**10**	**11**	**12**	**Heating season**
$\langle T_0 \rangle$ (°C)	1.6	3.2	7.2	11.7	10.6	5.9	2.1	4.5
$COP_{stea,mean}$	2.62	2.71	2.93	3.19	3.13	2.86	2.65	2.8
COP_{dyn}	2.65	2.68	2.79	2.91	2.73	2.82	2.68	2.7
Rel. difference	**1 %**	**-1 %**	**-5 %**	**-9 %**	**-14 %**	**-1 %**	**1 %**	**-3 %**
$1-\langle T_0 \rangle/T_i$	0.058	0.053	0.039	0.024	0.027	0.044	0.057	0.049
$\langle 1-T_0(t)/T_i(t) \rangle$	0.062	0.061	0.055	0.047	0.058	0.053	0.061	0.059
Rel. difference	**7 %**	**13 %**	**29 %**	**50 %**	**53 %**	**17 %**	**7 %**	**18 %**
$\psi_{stea,mean}$	0.153	0.144	0.115	0.076	0.086	0.125	0.150	0.135
ψ_{dyn}	0.162	0.160	0.149	0.136	0.157	0.145	0.159	0.157
Rel. difference	**9 %**	**10 %**	**23 %**	**44 %**	**45 %**	**14 %**	**6 %**	**14 %**

Table 3 Comparison between steady state evaluation based on monthly mean temperatures from weather file and dynamic evaluation for Milano

	Monthly mean from standard				**Monthly mean from weather file**			
Month	**1**	**2**	**12**	**Heating season**	**1**	**2**	**12**	**Heating season**
$\langle T_0 \rangle$ (°C)	11.1	11.6	12.6	12.1	12.8	13.0	14.1	13.4
$COP_{stea,mean}$	3.15	3.18	3.24	3.21	3.25	3.26	3.32	3.28
COP_{dyn}	3.15	3.11	3.25	3.17	3.15	3.11	3.25	3.17
Rel. difference	**0 %**	**-2 %**	**0 %**	**-1 %**	**-3%**	**-5%**	**-2%**	**-4%**
$1-\langle T_0 \rangle/T_i$	0.026	0.024	0.021	0.023	0.020	0.020	0.016	0.018
$\langle 1-T_0(t)/T_i(t) \rangle$	0.035	0.037	0.028	0.033	0.035	0.037	0.028	0.033
Rel. difference	**25 %**	**35 %**	**27 %**	**33 %**	**42%**	**47%**	**45%**	**46%**
$\psi_{stea,mean}$	0.082	0.077	0.067	0.072	0.065	0.064	0.052	0.059
ψ_{dyn}	0.102	0.110	0.088	0.100	0.102	0.110	0.088	0.100
Rel. difference	**20 %**	**30 %**	**24 %**	**28 %**	**36%**	**42%**	**41%**	**41%**

Table 4 Comparison between steady state evaluation based on monthly mean temperatures from standard/from weather file and dynamic evaluation for Palermo

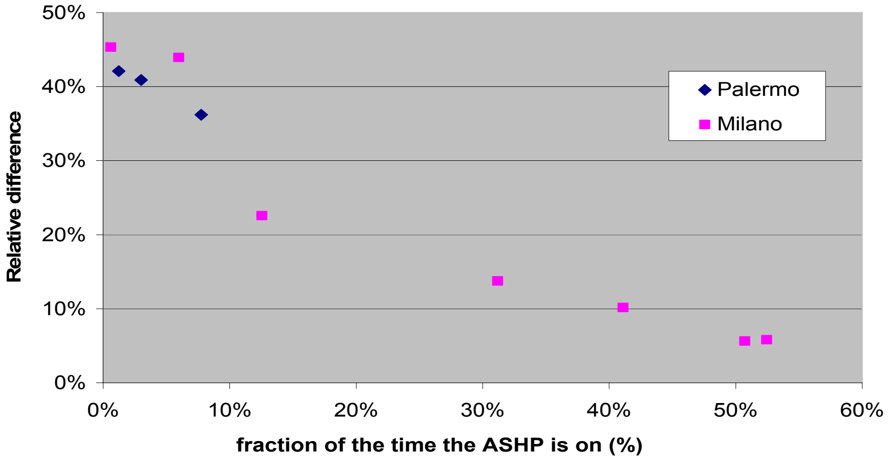

Fig 3. Relative difference between steady state analysis based on monthly mean temperatures (weather file) and dynamic one, vs the fraction of the time the ASHP is on

Regarding the opportunity to adopt monthly mean outdoor temperatures from the weather file used in the dynamic simulations rather than from the standard, we may notice that in Milano this choice would reduce the seasonal relative difference, in absolute value, from 24 % to 14 % (Table 2 and Table 3), while in Palermo it would increase it from 28 % to 41 % (Table 4). The opposite trends may be explained noticing that passing from the standard to the Meteonorm weather file data means moving to higher reference temperatures in Milano and to lower in Palermo. Therefore no general recommendations can be derived.

Conclusions and developments

Despite dynamic approach could be time consuming and complex, this analysis puts in evidence the importance of adopting it if one of the following conditions occurs:

- the cooling season is considered;
- the climate of the site is not so extreme or, in other words, the system is expected to work for a small fraction of the time.

In the remaining situations, such as for heating evaluations in cold climates, discrepancies between dynamic and steady state evaluations are significant but not dramatic. Anyhow some criteria upon which the discrepancy could be defined acceptable should be set. A possibility would be to verify if this discrepancy would affect a comparison among different heating systems based on their exergy efficiency. Therefore a further development of this study could extend the analysis to other kinds of HVAC systems, in order to understand if adopting a steady state or a dynamic approach for exergy efficiency calculation would influence the choice of the systems. Furthermore, other developments could be previewed for extending the boundary of the analysis, including not only the building step (envelope and system) but also the energy generation plant step (i.e. electricity generation for feeding the heat pump), where actually a significant fraction of the overall exergy destruction may occur.

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