For the Calculation of the Exergy Value of Indoor Air in Buildings

Selection of a Reference Environment

As an initial step of exergy application for building design, a reference environment of buildings needs to be properly defined. Since properties of (indoor) air play a vital role in indicating indoor thermal comfort, health and energy use, air seems to be the most important and appropriate medium for investigating some of the possible definitions of the reference environment to determine the exergy value of air in buildings. The most reasonable reference environment for calculating the exergy values of air in buildings is the actual environmental conditions of the air outside the buildings. However, building designers may find using the actual outdoor environmental condition too complex for exergy calculations. In the practice of building design, the exergy of air in a building should be estimated in an easy, less time-consuming way, and as precisely as possible.


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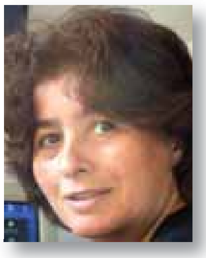
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Several authors (e.g. [1-4]) have used an exergy approach to evaluate thermodynamic processes in HVAC systems, but most of them used fixed or time-independent values of outdoor climate conditions (e.g. temperature at 273,15K and pressure at 1,01325bar) as a reference environment. The outdoor climate conditions vary in reality continuously, all over the year. The use of pre-defined standard conditions instead of this dynamic reference environment could lead to inaccurate results. Besides, the exergy calculation methods rely on several properties of the reference environment, like temperature, pressure and chemical composition. Most research into exergy and buildings only takes account of the thermal exergy of air [5-8]. From the work of [1 and 9] it appears however that these assumptions may lead to less accurate results.

The objective of this paper is to determine the exergy of air in buildings, considering also the chemical contribution, and to illustrate differences in exergy values of air in buildings in two different places on earth located in different climate zones. The paper critically analyses the influence of possible definitions of the reference state to determine the exergy of air in buildings, considering two different parameters (air temperature T and humidity ratio of humid air W). This paper takes the real environment of the buildings as the reference state to calculate the thermal and chemical contributions to the exergy value of air. The paper first considers all two exergy contributions, and then goes on to discuss the influence of not or only partly taking into account of the humidity of air in exergy calculations, to investigate the possibility of considering the indoor air and the outdoor air as dry air for exergy calculations. The exergy calculations use specific indoor climate conditions of a general ther-

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mal comfort zone, and use outdoor climate conditions of two cities in different climate zones. The exergy calculations are made on an hourly basis, using hourly indoor and outdoor climate data. The exergy results are presented as average values and used for the discussions.

EXERGY OF A SUBSTANCE

The magnitude of the exergy value of a substance can be regarded as the sum of the physical and the chemical contributions. The physical exergy refers to the departure of the physical state of the system, at a certain pressure and temperature, compared with that of the reference environment. The chemical exergy refers to the departure of the chemical composition of a system, at the reference temperature and pressure, from that of the reference environment.

Physical exergy

Physical exergy (Ex_{ph}) is equal to the maximum amount of mechanical work obtainable when a substance is brought from its initial state temperature T and pressure P, to the state of the reference environment defined by T_o and P_o. For a process stream, the physical exergy could be calculated by using equation 1.

$$dEx_{ph} = dH - T_o dS + dKE + dPE \qquad (1)$$

In equation 1 H is the enthalpy, S is the entropy, KE is the kinetic energy and PE is the potential energy of that process stream. Subscript o indicates that the properties are in the state of the reference environment. Exergy calculations are generally often performed under conditions where the kinetic and potential terms can be ignored [10]. It is assumed that potential and kinetic energy contributions to the exergy value of air in the buildings can be ignored. Equation 1 then reduces to equation 2 [11].

$$dEx_{ph} = dH - T_o dS \qquad (2)$$

By using the perfect gas laws in equation 2 and assuming a constant molar isobaric heat capacity (c_p) the molar physical exergy value follows from equation 3:

$$dEx'_{ph} = c_p dT + \frac{RT_o}{P} dP - T_o \frac{c_p dT}{T} \qquad (3)$$

Therefore, the molar physical exergy value with the reference environment T_o and P_o is

$$Ex'_{ph} = c_p\left((T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right) + RT_o \ln\left(\frac{P}{P_o}\right) \qquad (4)$$

In equation 4, the first term, in the large brackets and multiplied by c_p, can be referred to as a thermal exergy value (Ex_{th}) and the second term can be called a change in exergy related to pressure differences, a mechanical exergy value (Ex_{me}).

Chemical exergy

Chemical exergy (Ex_{ch}) is equal to the maximum amount of mechanical work obtainable when a substance under consideration is brought from the state of the reference environment to the dead state by processes involving heat transfer and exchange of substances only with the dead state [12]. The final state will be what is called "dead state", which means that all substances are in thermal, mechanical and chemical equilibrium in this state.

The exergy of the outdoor air, which is the reference environment, is strictly speaking not zero; work could be obtained if the substance were to come to thermal, mechanical and chemical equilibrium. Many chemical reactions in the reference environment are blocked because the activation energy is so great that the chemical reactions to more stable substances cannot occur at environmental conditions [13]. In this work, chemical exergy is defined as the difference between the exergy content of air in buildings and the exergy content of the outside air (as the reference environment), which is not in the dead state. The air components considered in this study are dry air and water vapour. The other components in the air (CO_2, H_2 etc.) are assumed identical in indoor and outdoor conditions. Their contribution to the exergy can therefore be neglected.

The contribution to the chemical exergy value of air due to mixing of dry air and pure water vapour in the case of an ideal mixture (air at T_o and P_o) is given by equation 5 [14], [1], [9].

$$\Delta Ex'_{mix} = RT_o \sum_{i=1}^{n} x_i \ln(x_i) \qquad (5)$$

where x_i is the mole fraction of the i-th substance and R is the molar gas constant (8.314 $Jmol^{-1}K^{-1}$).

EXERGY OF AIR IN BUILDINGS

The molar exergy value of humid air in buildings can be calculated as the total of its physical exergy ($Ex'_{ph,humidair}$) and its chemical exergy ($Ex'_{ch,humidair}$), using equations 6 and 7 [1], [15], [14]. Equation 6 is derived from equation 4 and equation 7 from equation 5.

$$Ex'_{ph,humidair} = \left((1 - x_s)c_{p,dryair} + x_s c_{p,s}\right)\left((T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right) + RT_o \ln\left(\frac{P}{P_o}\right) \ [J/mol] \qquad (6)$$

$$Ex'_{ch,humidair} = RT_o\left(x_s \ln\left(\frac{x_s}{x_{s,o}}\right) + (1 - x_s)\ln\left(\frac{1 - x_s}{1 - x_{s,o}}\right)\right) \ [J/mol] \qquad (7)$$

where x_s is the mole fraction of water vapour in indoor air, $c_{p,dryair}$ is a constant molar isobaric heat capacity of dry air, $c_{p,s}$ is a constant molar isobaric heat capacity of water in the vapour phase, and T and P are the temperature and pressure of the indoor air. Subscript o indicates that the properties are in the state of the reference environment.

Because building engineers and designers prefer to use kilograms instead of moles, equations 6 and 7 are hereunder converted to J/kg. The mole fractions of water vapour in air x_s and of dry air x_{dryair} are related to the humidity ratio W [16]. In this work, the humid air is considered as a two-component mixture of dry air and water vapour. The molar mass of dry air and of water vapour is 0,0290 kg/mol and 0,0180 kg/mol respectively [16]. The exergy value of humid air in buildings (per kilogram of humid air) can be calculated, as functions of air temperature T and humidity ratio W, by using equation 8 and 9.

(8)

$$Ex_{ph,humidair} = \left(\frac{0,62198c_{p,dryair} + Wc_{p,s}}{0,62198 + W}\right)\left((T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right) + R\left(\frac{1+W}{34,5224 + 55,5081W}\right)^{-1} T_o \ln\left(\frac{P}{P_o}\right) \quad [\mathrm{J/kg}]$$

(9)

$$Ex_{ch,humidair} = R\left(\frac{1+W}{34,5224 + 55,5081W}\right)^{1} T_o\left(\left(\frac{W}{0,62198 + W}\right)\ln\left(\frac{W}{W_o}\right) + \ln\left(\frac{0,62198 + W_o}{0,62198 + W}\right)\right) \quad [\mathrm{J/kg}]$$

ASHRAE [16] recommends $c_{p,dryair}$ and $c_{p,s}$ as constant values (1,006 $\mathrm{kJkg^{-1}K^{-1}}$ for dry air and 1,805 $\mathrm{kJkg^{-1}K^{-1}}$ for water vapour). However, the molar isobaric heat capacity c_p is a function of temperature [15]. For air temperatures between ±50 °C, the average value of cp,dryair is 29,0167 $\mathrm{Jmol^{-1}K^{-1}}$ (1,0017 $\mathrm{kJkg^{-1}K^{-1}}$) and the average value of cp,s is 33,5408 $\mathrm{Jmol^{-1}K^{-1}}$ (1,8618 $\mathrm{kJkg^{-1}K^{-1}}$). The total change of $c_{p,dryair}$ is 2 % and the total change of $c_{p,s}$ is 0.8 %. The average values of $c_{p,dryair}$ and $c_{p,s}$ are used for this work.

APPROACH

The exergy value of indoor air (per kilogram of humid air) at specific indoor climate conditions is investigated as a function of different outdoor climate conditions. Reference environments, used for the exergy calculations, are actual outdoor climate, time-dependent, and from two cities in different climate zones. Differences in air properties (temperature T and humidity ratio W) between the indoor air and the outdoor air are variables for this study.

Indoor climate conditions, used in the exergy calculations, are air temperature T_i between 20-26 °C, relative humidity PH_i between 30-60 % and air pressure P_i equal to atmospheric pressure. The indoor climate conditions are commonly applied for an indoor thermal comfort zone. Figure 1 shows the area of the conditioned indoor climate on the ASHRAE psychometric chart [16].

A characteristic of the indoor climate conditions is that they are allowed to vary in a window of indoor air temperatures T_i and humidity ratios of the indoor air W_i. W_i can be obtained by using the ASHRAE psychometric chart or equations [16], as a relation of T_i and RH_i. Therefore W_i [kg water vapour/kg dry air] are between 0,0044-0,0088 where T_i is 20 °C and RH_i is between 30-60 %. W_i is between 0,0064-0,0128 where T_i is 26 °C and RH_i is between 30-60 %. T_i is determined before determination of W_i, since W_i has a relation to T_i and RHi. To determine T_i the following rules are used

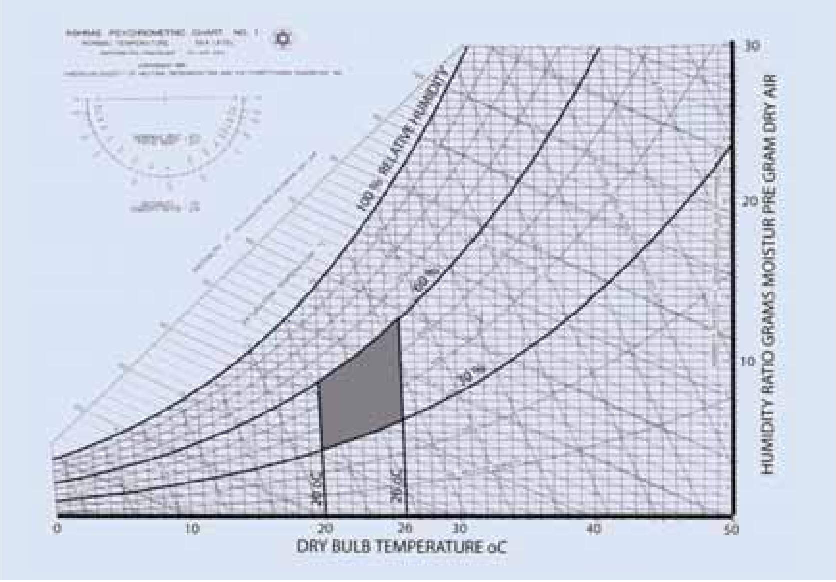
- If To ≥ 26 °C, then T_i = 26 °C (or, in other words, the temperature inside the building is maintained at 26 °C by HVAC equipment when the outside temperature is above 26 °C)
- If To ≤ 20 °C, then T_i = 20 °C (or, in other words, the temperature inside the building is maintained at 20 °C by HVAC equipment when the outside temperature is below 20 °C)
- If 20 < To < 26 °C, then $T_i = T_o$ (the indoor and outdoor temperatures are equal)

To determine Wi identical rules are used, but the upper and lower bounds of W_i must be determined at T_i = 20 °C and then at T_i = 26 °C. W_i can then be determined in the same way as T_i before.

If $W_o \geq W_{i,\max}$, then $W_i = W_{i,\max}$
If $W_o \leq W_{i,\min}$, then $W_i = W_{i,\min}$
If $W_{i,\min} < W_o < W_{i,\max}$, then $W_i = W_o$

Outdoor climate conditions, used in the exergy calculations, are from two different places in different climates (a cold climate, De Bilt NL; and a hot and humid climate, Bangkok TH). Climate data from these sites are taken from the TMY2 data [17]. The data represent air temperatures, humidity ratios and atmospheric pressures, on an hourly basis. Characteristics of the outdoor climate conditions are presented in the next chapter.

The analysis framework in figure 2 is used to study the influence of possible definitions of a reference environment on the exergy of air in buildings. The analysis framework considers exergy values of air in buildings, calculated by using different given reference environment alternatives, to investigate what reference environment alternative might be able to substitute the actual reference environment depending on all air properties (T, W and P). The analysis framework also considers the exergy values of air in buildings at different levels of humidity, by assuming $W_i = W_o$ and $W_i = W_o = 0$, with the other reference environment parameters remaining the same defined conditions of the indoor air and outdoor air. The aim is to investigate the possibility of considering indoor air and outdoor air as dry air for exergy calculations.



The conditioned indoor climate area given on the ASHRAE psychometric chart.

- FIGURE 1 -

The exergy calculations are performed for three calculation options:

- calculation option A $Ex(T_i,W_i,P_o)$: exergy calculation of humid air in buildings, assuming $P_i = P_o$, using equations 11 and 12, i.e. neglecting pressure differences between indoor and outdoor air;
- calculation option B $Ex(T_i,W_o,P_o)$: exergy calculation of humid air in buildings, assuming $P_i = P_o$ and $W_i = W_o$, using equation 14, i.e. neglecting differences in pressure and humidity ratio between indoor and outdoor air;
- calculation option C $Ex(T_i,0,P_o)$: exergy calculation of dry air in buildings, assuming ${}_i = P_o$ and $W_i = W_o = 0$, using equation 15.

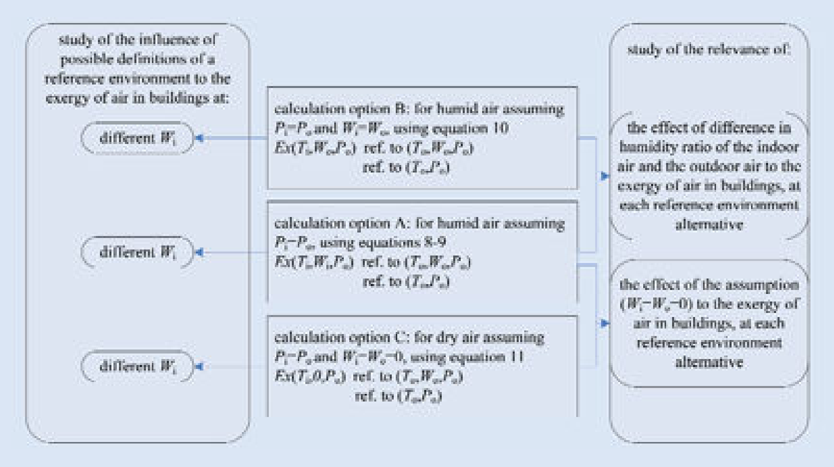
Equations 14 and 15 are derived from equations 10 and 11.

$$Ex = \left(\frac{0.62198c_{p,dryair} + W_o c_{p,v}}{0.62198 + W_o}\right)\left((T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right) \quad (10)$$

$$Ex = c_{p,dryair}\left((T - T_o) - T_o \ln\left(\frac{T}{T_o}\right)\right) \quad (11)$$

Since it is assumed that there is no pressure difference between the indoor air and the outdoor air, two possible reference environment alternatives are defined as combinations of the air parameters (T, W and P), to be used in this framework. The reference environment alternatives considered are the following:

- reference environment alternative 1 (T_o,W_o,P_o): air temperature T_o, humidity ratio of air W_o and air pressure P_o;
- reference environment alternative 2 (T_o,P_o): air temperature T_o and air pressure P_o.



Analysis framework to study the influence of possible definitions of a reference environment to determine the exergy of air in buildings.

- FIGURE 2 -

Differences between exergy results, made by using a calculation option with all reference environment alternatives, are investigated in order to identify what reference environment alternative might be able to substitute the actual reference environment (reference environment alternative 1), within the assumptions of the calculation option. Chemical contribution to the exergy value of the air can be obtained as difference between the exergy results using reference environment alternatives 1 and 2. The rest of the contributions to the exergy value of the air is the thermal contribution.

Differences between exergy results, obtained by using calculation option A and B with a similar reference environment alternative, are investigated to identify the possibility of neglecting the difference between W_i and W_o for the exergy calculations.

Differences between exergy results, obtained by using the calculation option A and C with a similar reference environment alternative, are investigated to identify the possibility of considering indoor air and outdoor air as dry air for the exergy calculations.

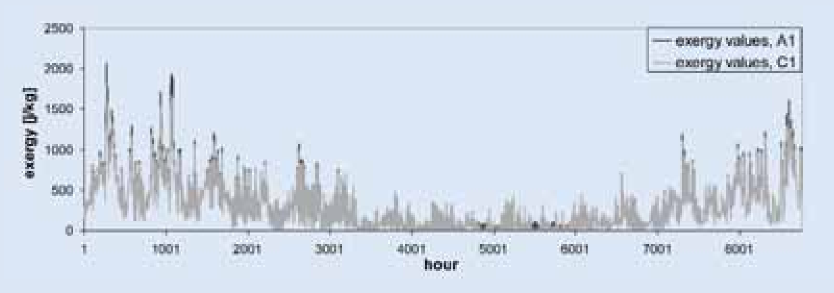
The exergy calculations are made for every hour in the typical meteorological year (TMY), by using hourly changing indoor and outdoor climate data. Hourly indoor climate data are determined by using the hourly outdoor climate data, as explained above. For

		Air temperature *T* [°C]			**Humidity ratio *W* [-]**		
		Season I	**Season II**	**Year**	**Season I**	**Season II**	**Year**
Outdoor	Average	14,99	5,31	9,37	0,0081	0,0046	0,0061
	Mode	13,55	0,60	6,50	0,0087	0,0037	0,0037
	Median	14,84	5,35	9,34	0,0079	0,0045	0,0057
	Standard deviation	4,84	5,28	6,99	0,0020	0,0015	0,0024
Indoor	Average	20,38	20,00	20,16	0,0077	0,0051	0,0062
	Mode	20,00	20,00	20,00	0,0088	0,0044	0,0044
	Median	20,00	20,00	20,00	0,0079	0,0045	0,0057
	Standard deviation	1,17	0,02	0,78	0,0016	0,0010	0,0018

Air temperature and humidity ratio at De Bilt.

- TABLE 1 -

the sake of clarity, the exergy results are presented as average values per season and for the TMY (8.760 hours). In this study, the TMY is divided into two seasons: Season I is defined as the period from 1 May to 30 September of the TMY (3.672 hours); Season II is defined as the remaining period of the TMY (5.088 hours). The average values of the exergy results are used for the discussions (see figure 4).



Hourly profiles of exergy calculation results for the TMY year, calculated by taking calculation option A with reference environment alternative 1 (line A1) and calculation option C with reference environment alternative 1 (line C1).

- FIGURE 3 -

Calculation option	Reference environment alternative	Season I	Season II	Year
A (humid air)	1	85,37	439,60	291,12
A (humid air)	2	81,12	426,42	281,68
B (humid air; W_i=W_o)	1,2	81,12	426,33	281,63
C (dry air)	1,2	81,00	425,93	281,34

Exergy of air in buildings in De Bilt (average values, in J/kg).

- TABLE 2 -

CASE STUDY

In the next sections the climate characteristics of two different locations are shown, as well as the tabulated results of the exergy calculations. These results are then analysed and compared.

Cold climate, De Bilt NL

De Bilt is located at 52°12’ north, 5°18’ east. Average, mode, median and standard deviation values of air temperatures *T* and of humidity ratios *W* at the city, per season and of the TMY, are given in table 1. These values are derived from the climate data at that site, taken from the TMY2 data [17].

Exergy values of air in buildings in the city are calculated for every hour in the TMY, by using combinations of the calculation options and the reference environment alternatives, mentioned in the previous section. An example of an exergy calculation is given below. Note that the average values given in tables 1 and 3 are not used in the calculations. The hourly values of the TMY are used.

Exergy of air in buildings in De Bilt at the first hour of the TMY is calculated by taking calculation option A with reference environment alternative 1 (using equations 8 and 9) and using the following data. The outdoor climate data are taken from the TMY2 data [17]. The indoor climate data are derived from the conditions explained in the previous section.

Outdoor air: T_o = 281,95 K, W_o = 0,00613, P_o = 100.800 Pa
Indoor air: T_i = 293,15 K, W_i = 0,00613, P_i = 100.800 Pa
Constant values: $c_{p,dryair}$ = 1,0017 kJkg^{-1}K^{-1}, $c_{p,s}$ = 1,8618 kJkg^{-1}K^{-1}, R = 8,314 Jmol^{-1}K^{-1}

This calculation is then repeated for each hour of the TMY year. Figure 3 shows the hourly exergy calculation results for the TMY year, calculated by taking calculation option A with reference environment alternative 1 (line A1) and calculation option C with reference environment alternative 1 (line C1).

Average values of the exergy values of air in the buildings per season and of the TMY are calculated from the sum of the hourly exergy calculation results, shown in table 2.

$$\begin{aligned}
Ex_{ph,humidair} &= \left(\frac{(0.62198)(1.0017)+(0.00613)(1.8618)}{0.62198+0.00613}\right)\left(293.15-287.15\ -(287.15)\ln\left(\frac{293.15}{287.15}\right)\right)\\
&\quad +(8.314)\left(\frac{34.5224+(55.5081)(0.00613)}{1+0.00722}\right)(287.15)\ln\left(\frac{100800\text{ Pa}}{100800\text{ Pa}}\right)\\
&= 0.21799\text{ kJkg}^{-1}\\
Ex_{ch,humidair} &= (8.314)\left(\frac{34.5224+(55.5081)(0.00613)}{1+0.00613}\right)(281.95)\left(\left(\frac{0.00613}{0.62198+0.00613}\right)\ln\left(\frac{0.00613}{0.00613}\right)+\ln\left(\frac{0.62198+0.00613}{0.62198+0.00613}\right)\right)\\
&= 0\text{ Jkg}^{-1}\\
Ex_{humidair} &= Ex_{ph,humidair}+Ex_{ch,humidair}\\
&= 0.21799+0\text{ kJkg}^{-1}\\
&= 0.21799\text{ kJkg}^{-1}
\end{aligned} \tag{12}$$

		Air temperature *T* [°C]			**Humidity ratio *W* [-]**		
		Season I	**Season II**	**Year**	**Season I**	**Season II**	**Year**
Outdoor	Average	28,30	27,28	27,71	0,0185	0,0166	0,0174
	Mode	27,90	27,85	26,50	0,0205	0,0150	0,0150
	Median	28,25	27,33	27,75	0,0184	0,0164	0,0175
	Standard deviation	2,70	3,37	3,15	0,0019	0,0026	0,0025
Indoor	Average	25,71	25,18	25,40	0,0126	0,0123	0,0124
	Mode	26,00	26,00	26,00	0,0128	0,0128	0,0128
	Median	26,00	26,00	26,00	0,0128	0,0128	0,0128
	Standard deviation	0,70	1,49	1,25	0,0004	0,0010	0,0008

Air temperature and humidity ratio at Bangkok.
- *Table 3* -

Calculation option	**Reference environment alternative**	**Season I**	**Season II**	**Year**
A (humid air)	1	169,00	110,32	134,91
A (humid air)	2	20,17	16,71	18,16
B (humid air; $W_i=W_o$)	1,2	20,20	16,73	18,19
C (dry air)	1,2	20,11	16,66	18,10

Exergy of air in buildings in Bangkok (average values, in J/kg).
- *Table 4* -

By multiplying the exergy values by the total number of hours of the season (3.673 for season I, 5.088 for season II and 8.760 for the total year), the total exergy losses can be easily calculated.

Hot and humid climate, Bangkok TH

Bangkok is located at 13°45' north, 100°31' east. Average, mode, median and standard deviation values of air temperatures *T* and of humidity ratios *W* at the city, per season and of the TMY, are given in table 3. These values are derived from the climate data at the site, taken from the TMY2 data [17].

Average values of exergy values of air in buildings in Bangkok per season and of the TMY are calculated from hourly exergy calculation results, shown in table 4.

Analysis and comparison of the results

Under the assumption of identical indoor and outdoor air pressure, considering humid indoor air (calculation option A) with humid outdoor air as reference environment alternative 1 leads to the most accurate determination of the exergy contents of indoor air. When the humidity of the reference environment is neglected, using reference environment alternative 2, differences in average values of the hourly exergy calculation results for season I may be very high (88,1 % for a hot and humid climate, but only 5,0 % for a cold climate). For season II and for the whole year, differences in average values of the exergy results are low for the cold climate (3,0 % and 3,2 % respectively), but very high for the hot and humid climate (84,9 % and 86,5 % respectively). Therefore, when dealing with humid air inside, with a humidity ratio different from the reference environment, the reference environment should also consists of humidity ratio of air *W*, because the chemical contribution to the exergy value is relatively high compared with the thermal contribution. This is particularly important for buildings with dehumidifying/humidifying equipment, air-cooling and also for buildings with a high occupancy level and a low level of moderate ventilation rate, because of the humidity production of occupants.

Exergy calculations using calculation options B and C, with reference environment alternative 1, gives more or less the same exergy results, since average values of *W*, per season and of the year, are very small, less than 0,0101.

When the humidity is assumed to be identical indoor and outdoor (calculation options B) which will be the case of well-ventilated buildings with a low occupancy (hence a low water vapour production), it is not necessary to chose humid air as the reference environment. A reference environment consisting of dry air is accurate enough and the indoor air itself may be considered as dry air too (calculation option C). These results are valid for all the studied types of climate.

CONCLUSIONS

The paper presents the analysis results of the exergy determination of air in buildings. The exergy determination is examined for combinations of the outdoor climate conditions of some climate zones (a cold climate zone, De Bilt NL; and a hot and humid climate zone, Bangkok TH), with specific indoor climate conditions. The reference environment for humid air, used for the exergy analysis, is determined by three parameters of air properties (temperature *T*, humidity ratio *W* and pressure P). The influence of possible definitions of a reference environment to determine the exergy of air in buildings is studied, considering the relevance of the effect of temperature and humidity ratio of the air.

The chemical contribution to the exergy value of air in buildings might, in some cases, be negligible for the exergy calculation of air in the buildings, depending on the season and the type of climate. In a cold climate the chemical contribution is relatively small compared with the thermal contribution. However, the chemical contribution is rather large in a hot and humid climate. The exergy calculation in a cold country might use only environmental temperature as a characteristic of the reference environment, and assume that the outdoor air and the indoor air are completely dry. In a hot and humid country these assumptions could lead to very large discrepancies and are therefore not recommended.

It is recommended to pay attention to this accuracy problem when exergy chains are calculated in buildings [5;7 en 8] because the share of exergy losses throughout the exergy chain could change strongly according to the chosen reference and indoor air properties. This will be the case in particular when humidifiers and dehumidifiers are used.

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