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# Modelling and simulation of HAM processes

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## Abstract

*The influence of the bioclimatic elements upon the building behavior is analyzed using Matlab/ Simulink and toolbox HAMBASE. However, this software does not take into account a crucial element characteristic of these bioclimatic buildings, the air density. We propose an enhancement of existing computer code by adding a model to calculate the air density characteristic along the already existing building simulation code. The validation of the new computational model consists in comparing the two models (with and without the air density equation) in standard test conditions recommended in ASHRAE Bestest 140/2001. Changes were obtained for the output parameters of this model (indoor resultant temperatures, heat losses) of up to 15%.*

## Rezumat

*Influența elementelor bioclimatice asupra comportamentului clădirii, sunt analizate cu ajutorul programului Matlab/Simulink si a bibliotecii HAMBASE. Totusi acest soft nu ia in calcul un element primordial caracteristic acestor cladiri bioclimatice, densitatea aerului. Propunem o amplificare a codului de calcul existent prin adaugarea unui model de calcul a densitatii aerului caracteristic acestor cladiri climatice. Validarea noului model de calcul, consta in comparatia celor doua modele (cu si fara ecuatia de calcul a densitatii aerului) in conditiile de testare recomandate in standardului ASHRAE Bestest 140/2001. S-au obtinut schimbari ale parametrilor de iesire din acest model (temperaturi rezultante interioare, pierderi de caldura) de pana la 15%.*

**Keywords:** HAM modelling, simulation programs, energy efficiency, bioclimatic buildings

## 1. Introduction

The use of bioclimatic elements inside building is a new philosophy for modern buildings [1] due to its response to both energy efficient trend [2] and high indoor air quality conditions [3]. Computer software is often used to understand the building energy consumption behavior and the variation of different indoor environment parameters. The most complex software for the building behavior simulation take into account the HAM (heat, air and moisture) models [4], like as: B-sim, ESP-r, EnergyPlus, TRNSYS and SPARK, BUILDINGS library, CARNOT and SIMBAD. The need for achieving the goal of developing a model study of elastic bioclimatic building, complete, complex, and easy to use, lead to the development of a new library developed in Matlab©/ Simulink®: HAMBASE [5]. The main advantages of HAMBASE are: (1) realistic simulation of building

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system dynamics (time step less than one hour), (2) reduced simulation time by modeling the heat flow that vary slowly and (3) include the transfer of moisture (water vapor) [6]. Although it has HAM models well developed, however it does not contain the formula that defines the relationship between density, temperature and relative humidity with negative influence on both the estimation of energy consumption and the indoor air parameters in the bioclimatic buildings. In this study we amplified the existing HAMBASE code by adding this new formula. A validation of the already existing software and the amplified one will be carried out in accordance with ASHRAE Standard 140/2001 [7].

## 2. HAM models

HAM (Heat, Air and Moisture) processes refer to the transfer of heat, air and moisture through the building envelope elements and into the spaces defined by them. Thermal, moisture and air models are connected by relations of dependence of equations variables, equations that describe the models. In HAMBASE solving the system of differential equations is achieved with variable time step. Discrete equations are solved iteratively by one hour step. The building is considered as consisting of several zones (multizone), systems of equations are valid for each area.

**The thermal model** in HAMBASE considers indoor environment characterized by a single weighted thermal convection coefficient and one weighted thermal coefficient of radiation. Implicitly it is characterized by two components of temperature: indoor air temperature $\theta_a$ and "resultant" or "environmental" temperature $\theta_x$, which represents the primary approximation in HAMBASE. Both temperatures are considered to be uniformly distributed. Temperature $\theta_a$ is used to calculate losses by convection (ventilation, infiltration), the convective heat gains and a part of radiative heat gains. Temperature $\theta_x$ is the average temperature of all interior surfaces and it is used to calculate transmission losses and part of the heat gains by radiation. The link between the two temperatures is via a coupling coefficient [5]. The thermal model is described by the following equations:

$$\boldsymbol{\Phi_l + \Phi_s = \Phi_g + \Phi_p} \tag{1}$$

$$C_a \frac{d\theta_a}{dt} = L_{xa}(\theta_x - \theta_a) - \sum \Phi_{ab} + \Phi_c - \frac{h_{cv}}{h_r}\Phi_r \tag{2}$$

$$0 = L_{xa}(\theta_a - \theta_x) - \sum \Phi_{xy} + \Phi_r + \frac{h_{cv}}{h_r}\Phi_r \tag{3}$$

$$\Phi_{x1,2} + \frac{C_{x1,2}}{L_{x1,2}}\frac{d\Phi_{x1,2}}{dt} = C_{x1,2}\frac{d\theta_x}{dt} \tag{4}$$

$$q_{xy}(t_t) = a_1 \Delta U_{xy}(t_t) + \Delta q_{xy}(t_{t-1}) \tag{5}$$

$$\Delta q_{xy}(t_t) = U_{xy}\sum_{i=2}^{n+4} a_i \Delta\theta_{xy}(t_{t-i+2}) k \sum_{k=1}^{2} b_k \Delta q_{xy}(t_{t-k}) \tag{6}$$

where the indices l, s, g, p is the heat loss, heat storage, heat gains, heating/cooling equipments respectively, $C_a$ - heat capacity of air [J/K] $\Sigma\Phi_{ab}$ - heat flow due to air flow $\theta_b$ [W] $\Phi_r$ - total heat flux by radiation [W] $\Phi_c$ - total convective heat flux [W] and $\Sigma\Phi_{xy}$ - transmission heat flow to a zone with temperature $\theta_y$ [W], $\Delta q_{xy}(t_t)$ - density variation of heat flux at times $t_1$, $t_2$ etc., $t_d = n + \Delta t_d$ - time lag with n integer and $0 < \Delta t_d < 1$, $a_1 \dots a_{n+4}$ și $b_1$, $b_2$ - coefficients of the transfer function [5].

Equation (1) defines the thermal balance of a zone. Equations (2) and (3) define the heat transfer inside the zone. The heat flux density in the envelope can be divided into two parts: transmission and storage. Both can be described by equations of second order. The system of differential equations for the heat transfer inside one zone and heat flow stored into the envelope elements (equation (4)) are solved in Simulink S-function with a variable time step. For the transmission heat transfer through the envelope parts (equations (5) and (6)) as well as for determining the heat gains it is used an iterative function in Matlab, with one hour step.

**The moisture model** is similar to the thermal one. Given that the diffusion is insignificant in relation with the transfer by advection (ventilation), it is considered negligible. The moisture model is described by the following equations:

$$G_l + G_s = G_g + G_p \tag{7}$$

$$C_{va}\frac{dp_{va}}{dt} + \frac{dC_f^t p_{va}}{dt} = -\sum G_{ab} - \sum G_{xy} + G_p + G_g \tag{8}$$

$$G_{1,2} + \frac{1}{L_{v1,2}}\frac{dC_{v1,2}^t G_1}{dt} = \frac{dC_{v1,2}^t p_{va}}{dt} \tag{9}$$

where the indices l, s, g, p are the loss of moisture by advection, moisture storage, internal moisture sources, (des)humidification respectively, $p_{va}$ - pressure of vapors in air [Pa], $C_{va}$ - moisture storage coefficient of air [kg/Pa], $C^t_f$ - hygroscopic coefficient of the furniture [kg/Pa], $G_{xy}$ - vapor flow to the envelope [kg/s], $G_{ab}$ - vapor transfer by air flow [kg/s], $G_{1,2}$ - the vapor flow rate [kg/s], $L_{v1}$, $L_{v2}$ - vapor transfer coefficients [kg/sPa], $C_{v1}$,$C_{v2}$ - moisture storage coefficients of the material [kg/Pa]. Equation (7) defines the mass balance of a zone. Equation (8) characterizes moisture processes inside it. Moisture storage in the envelope parts is described similarly to heat storage, by the second order differential equations (9). The system of differential equations is solved by the S-function in Simulink [6]. As in the case of the thermal model, the vapor flows from internal sources are calculated with the step of one hour in a Matlab function.

**The air model** is represented as a network of pressure nodes, the building being divided into several cells (zones), represented by nodes interconnected by flow paths. The air model is described by the following equations:

$$D_m = \rho_a C(\Delta p)^n \tag{10}$$

$$\Delta p_{ij} = p_i + \rho_0 g h_k\left(\frac{1}{\theta_i + 273} - \frac{1}{\theta_j + 273}\right) - p_j \tag{11}$$

$$\Delta p_{ie} = p_i + \rho_0 g h_l\left(\frac{1}{\theta_i + 273} - \frac{1}{\theta_e + 273}\right) - \frac{1}{2}C_p\rho_a v_{wind}^2 \tag{12}$$

$$\sum_{j,k}\Delta p_{ij}C_{ijk}\left|\Delta p_{ij}\right|^{n_{ijk}-1} + \sum_{l}\Delta p_{ie}C_{iel}\left|\Delta p_{ie}\right|^{n_{iel}-1} + \sum_{j}\frac{D_{mi\to j} - D_{mj\to i}}{\rho_a} + \frac{D_{mi\to e} - D_{me\to i}}{\rho_a} = 0 \tag{13}$$

where $D_m$ is the air flow [kg/s], $\rho_{a,0}$ – actual/reference air density [kg/m$^3$], C - flow coefficient [m$^3$/sPa$^n$], $\Delta p$ - pressure difference in the opening [Pa], n - flow exponent [-, 0.5<n<1], $p_{i,j}$ - indoor pressures in zones i and j [Pa], g - acceleration due to gravity [9.81 m/s$^2$], $h_{k,l}$ - vertical distance between openings plans, internal or external and reference plan [m], $\theta_{i,j,e}$ - indoor temperatures in zones i and j, respectively outside temperature [°C], $C_p$ - wind pressure coefficient [-] $v_{wind}$ - wind speed [m/s], $\mathbf{D_{mi,j,e\to j,i,e}}$ - mechanical ventilation flow between zones and to/from outside [kg/s].

The general equation for determining airflow is equation (10). To achieve pressure differences at the inner and outer openings equations (11) and (12) are used. Determination of internal pressure for each zone is done by writing the mass balance of every node (equation (13)). After that the air

flows for infiltration/natural ventilation are easily determined.
**Newly introduced formula** of density [8] is:

$$\rho_a = \frac{\rho_0(\theta_0 + 273) - 0,00129 * p_{sa} * \varphi_a}{\theta_a + 273} \quad (14)$$

where $\rho_{a,0}$ is the effective/reference air density [kg/m$^3$], $\theta_{a,0}$ – effective/reference temperature of air [°C], $p_{sa}$ - vapor saturation pressure [Pa], $\varphi_a$ - relative air humidity [%].
Including this formula was necessary because the study aims to determine the influence of relative humidity and hence of the air density on the energy consumption and ventilation flows. This formula introduce another coupling relation between air and moisture models (density depending also on relative humidity), but it intervenes also in the heat and moisture capacity of air and hence in the air flow losses of the thermal and moisture models.

## 3. Simulation and validation

Validation was performed using ASHRAE Bestest 140/2001 standard, cases 600 (heating / cooling temperature control) and 600ff (without control of the interior parameters) [7]. Test chamber has dimensions considered in Figure 1 and the wall with windows facing south. The structure is light wood, materials with low thermal inertia. In terms of radiative properties, the opaque surface emissivity is considered 0.9 and the short wavelength absorption coefficient is 0.6. The windows are double-glazed with the transmission coefficient of 3.0 W/m$^2$K. Solar heat gain coefficient at normal incidence angle is considered 0.787 and shading coefficient is 0.916.

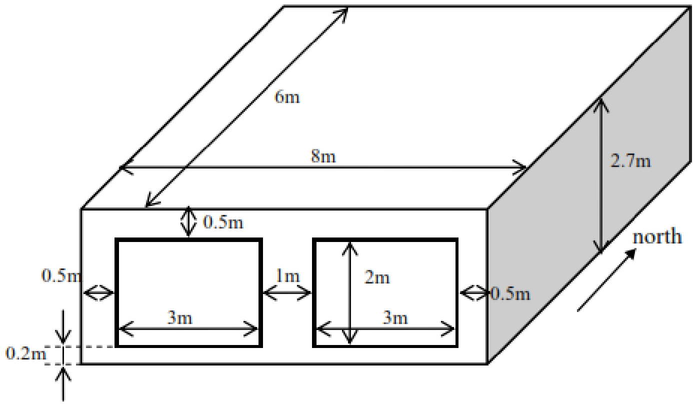


Figure 1. Reference building used in the ASHRAE Bestest 140/2001 [7]

Test chamber is considered to be located in Denver, United States of America, at an altitude of 1609m, 39.8° North latitude and 104.9° West longitude. Weather data describe an area with cold winters and sunny days (minimum -24.4°C) and hot and dry summers (maximum 35°C) with frequently clear sky. Soil temperature is considered constant and equal to 10°C. Internal heat gains are considered equal to 200W, 100% sensitive, 60% radiation and 40% convection. Test room ventilation rate is 0.5h$^{-1}$, taking into account a factor of 0.822 when calculating the volume for location at an altitude of 1609m. For case 600, control is performed at 20°C for the heating and 27°C for the cooling.
The used simulation programs are HAMBASE 2011 version and the new version modified by introducing density formula for temperature and relative humidity: HAMBASEρ. These, as previously detailed, are libraries developed in Matlab/Simulink, which can solve systems of differential equations and discrete equations described by HAM models.
For a period of 365 days both versions were run. Output results were averaged for each hour. They were highlighted during the whole year and for shorter periods in the graphs below. Hourly average values and annual amounts were compared among both versions and with the literature data.

The three elements of comparison between the two versions were indoor air temperature and heat loss through ventilation airflow for case 600ff, and energy consumption for heating and cooling for case 600. Also comparisons were made between values obtained in the two test cases for both libraries and the values available in [5] - HAMBASE version 2005, and [7] - limits proposed by ASHRAE, as shown in Figure 6.
The results obtained by comparing HAMBASE 2011 and HAMBASEρ, 600ff and 600 cases of ASHRAE Bestest 2011, can be seen in Figures 2 to 5.

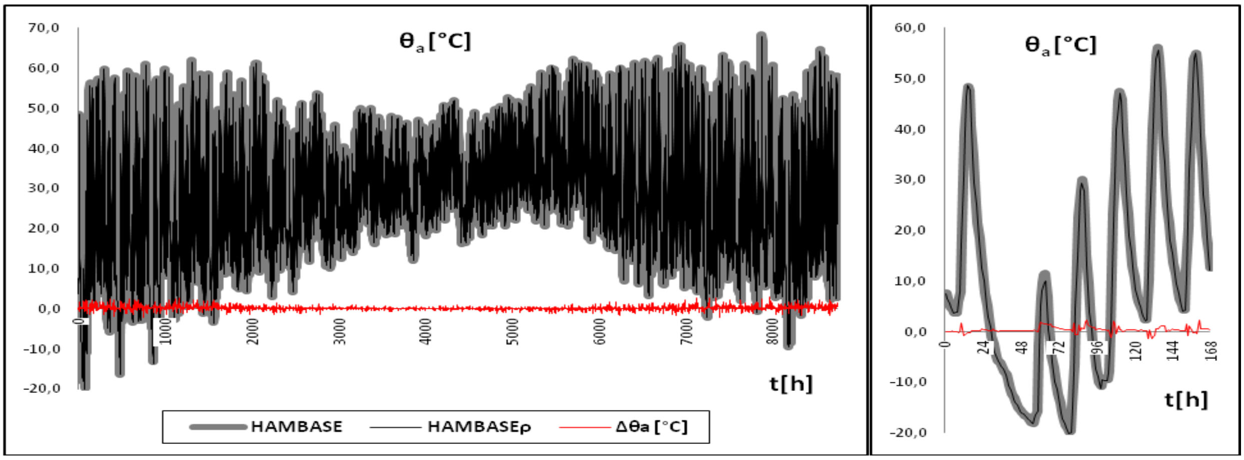


Figure 2. HAMBASE vs. HAMBASEρ - indoor air temperature (case 600ff)
for one year (left) / first week (right)

Between the two versions of HAMBASE there is a small variation of the indoor temperature $\theta_a$ (Fig. 2, if 600ff), the maximum difference $\Delta\theta_a$ being -2.2°C, respectively 2.9°C. Basically introducing the new formula influences the indoor temperature in an insignificant manner, small changes can be noticed, however, between the peak temperatures of each day. Average temperature variation between the two versions for a whole year lies around 0.1°C.

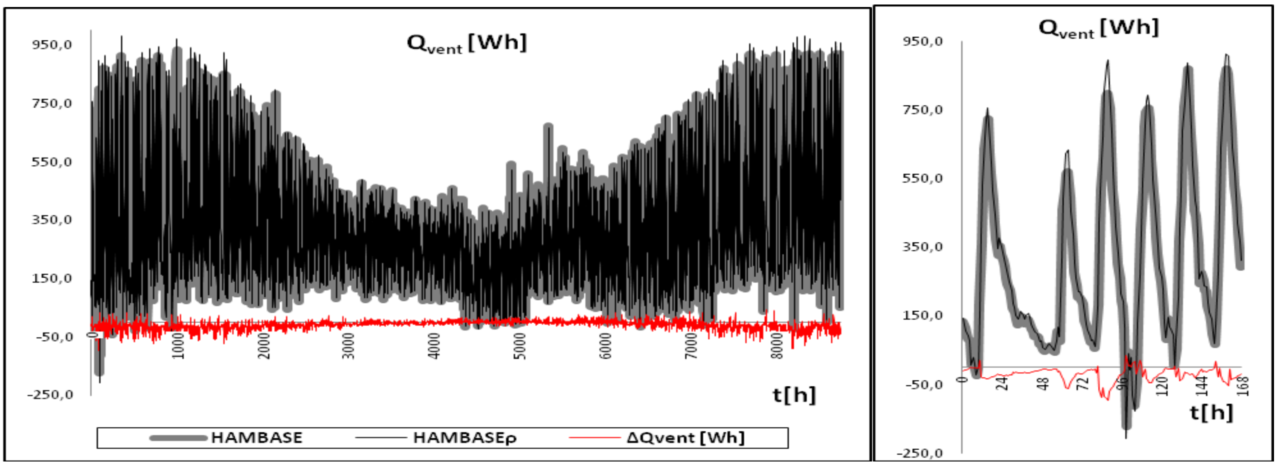


Figure 3. HAMBASE vs. HAMBASEρ - heat loss through ventilation air (case 600ff)
for one year (left) / first week (right)

For the heat loss through air ventilation $Q_{vent}$ (fig. 3), it may notice a more important variation of values, the maximum differences $\Delta Q_{vent}$ being -97.6Wh, 43.4Wh respectively. For one year these totalize -83.6kWh. It is noted that the winter variation is important because higher density and hence greater mass of ventilation air entering the building. Basically for the same given volume of $0.5h^{-1}$, the mass of introduced cold air increases with density, which in turn increases with decreasing temperature and relative humidity. This explains the sensitivity of the parameter heat loss through ventilation flow to density in HAMBASEρ.

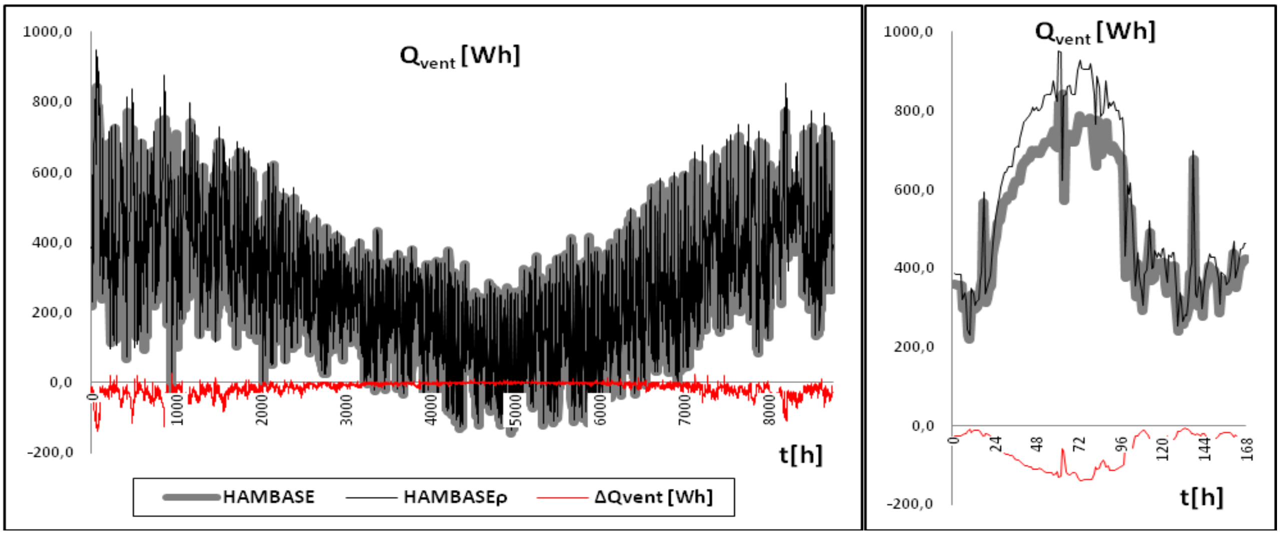


Figure 4. HAMBASE vs. HAMBASEρ - heat loss through air ventilation (case 600)
for one year (left) / first week (right)

For the case 600 (with control of the interior parameters), the difference is even more obvious (fig. 4), observing the maximum variation $\Delta Q_{vent}$ of -140.5Wh, 26.6Wh respectively. At the level of a full year the total difference lies around -138.1kWh, representing an error of about 6.2%. Values of $\Delta Q_{vent}$, higher in winter and lower in summer than for the case 600ff, are explained by different gaps of indoor/outdoor temperature and humidity in the two cases.

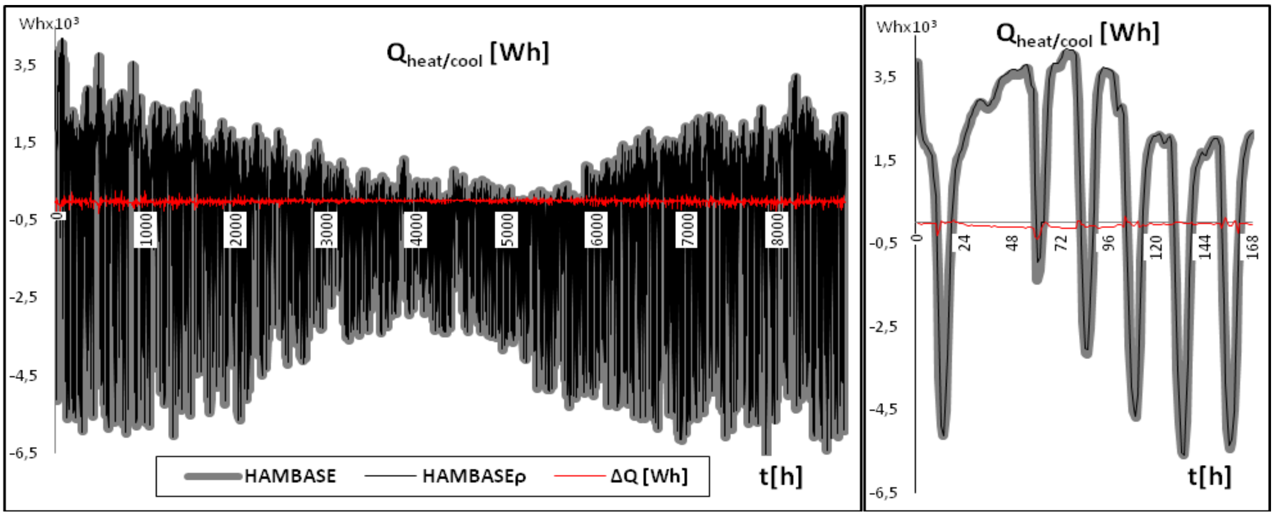


Figure 5. HAMBASE vs. HAMBASEρ - hourly loads heating/cooling (case 600)
for one year (left) / first week (right)

For the total energy consumption cooling/heating (fig. 5), differences ΔQ are noticeable, the maximum values being of -400.8Wh, 266.3Wh respectively. For one year the differences amount to -137.0kWh. Differences are observed especially at daily peak loads. Note that differences for an year of heat loss through air ventilation practically are identical to the differences of total energy consumption for heating/cooling, even if the maximum hourly differences don't agree.
In conclusion it can be stated that the introduction of the new formula for density in HAMBASE toolbox has led to an increased sensitivity to changes of temperature and humidity. If the indoor

temperature is not affected too obvious (case 600ff), the heat loss through ventilation flows and hence the total energy consumption (case 600) is quite influenced. It should be noted that the influence of density occurs in two interesting cases for the bioclimatic buildings: (1) in the summer when indoor temperatures are not controlled by elements of active equipments and ventilation flows are greater than $0.5h^{-1}$ of the current study and (2) in the winter, when the infiltration can lead to significant airflow and indoor air temperature is controlled around 20°C. Also after insertion of the new formula, the study of thermal, air and humidity effects dues to the introduction of vegetation into the zones of bioclimatic buildings becomes more realistic.
Comparing the results after running the two versions of HAMBASE with literature data, we obtain the diagram in figure 6.

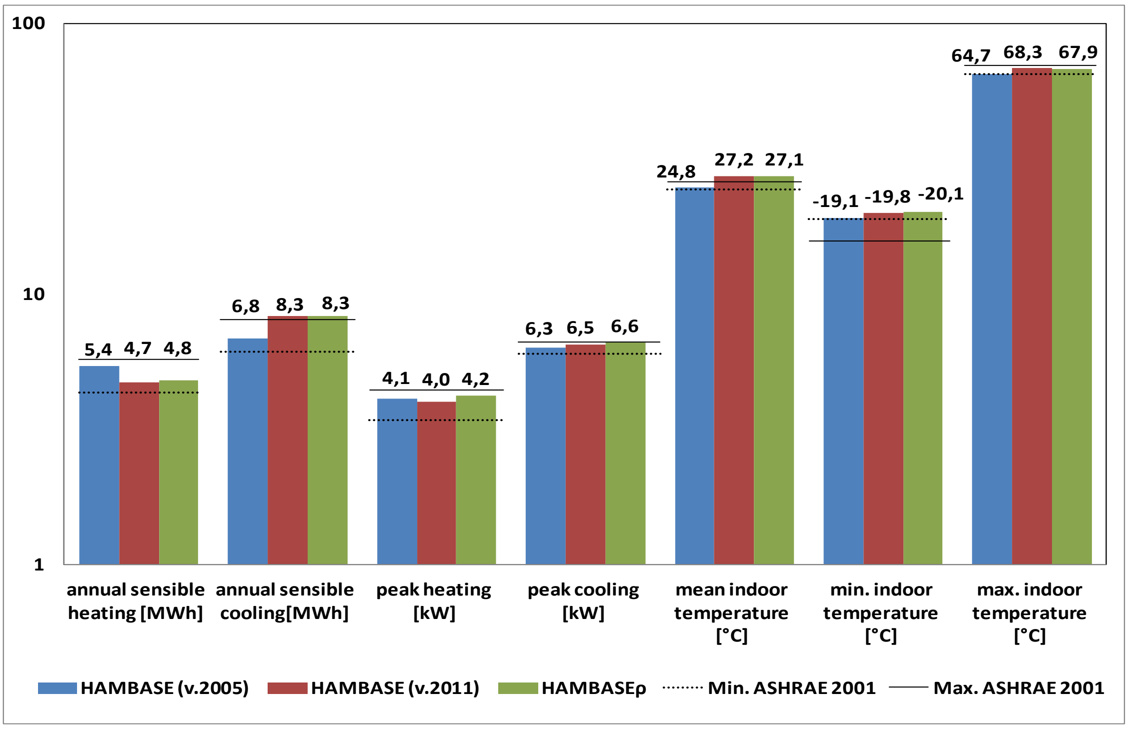


Figure 6. Comparison between different versions of Hambase vs. ASHRAE 140/2001 (logarithmic scale)

According to the diagram above, the results obtained with the two versions tested are close to the values of 2005 version of the toolbox (developed only in Matlab). Also they fit well within the interval suggested by ASHRAE Standard 140/2001. Compared to the 2011 version, HAMBASEρ is closer to the average indoor temperature interval proposed and a little bit further for the minimum indoor air temperature. For annual sensible cooling load it slightly exceeds the upper limit and for the other parameters of comparison values fall between the limits stated by the standard. HAMBASEρ can therefore be considered a valid HAM simulation toolbox.

## 4. Conclusions

HAMBASE toolbox was enriched by introducing the formula for calculating density depending on temperature and relative humidity resulting in HAMBASEρ. Functions of both libraries were run for the same test room. Simulation results were compared with each other and with results from the literature for simulation software approval. Equations of HAM models of the two versions were solved in the Matlab/Simulink with satisfactory computation speed, including runs for long periods (one year). The validation tests were carried out using ASHRAE Standard 140/2001, case 600 (with temperature control - maximum 27°C and minimum 20°C) and 600ff (without control of the interior parameters). Between the two versions was a small variation in the internal temperature, a greater variation of heat loss through air venting (both for case 600ff) and one noticeable for the heating/ cooling load (case 600). There was a good correlation between the results of the two versions tested with data from the literature.

In conclusion, HAMBASE 2011 toolbox was verified and completed. After running the validation tests according to ASHRAE Standard 140/2001, also the new toolbox HAMBASEρ has been validated. Further research on the HAMBASE involves the introduction of the vegetation models. Also case studies and sensitivity analyses will be conducted to determine the influence of vegetation on energy consumption and the indoor conditions of bioclimatic buildings.

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