Quantification of the internal space climate

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Abstract. A practicable model and program CLIMT is put forward for determining the hourly values of indoor air temperature and the interior air humidity in relation to the external climate, the building parameters (geometry, material properties), the ventilation and the use of the internal space (interior heat sources, moisture sources and heating system). In order to generate the outdoor climatic data (temperature, relative humidity, short and long wave radiation, precipitation, wind velocity and direction, driving rain) for the simulation a climate generator CLIG has been developed additionally. The results have been validated with measurements in actual buildings.

1 Introduction and climate boundary conditions

The developed simplified model and program **CLIMT (Climate-Indoor-Moisture-Temperature)** can be used for the calculation of the indoor climate components consisting of air temperature and air relative humidity [1,2]. At first it is necessary to provide the hourly values of the outdoor climate. Secondly, the geometry of the building, the construction of the building parts and the thermic and hygric material parameters must be given. Finally, all parameters of use – heating, inner heat and moisture sources, ventilation and the shadow equipment are necessary.

Before the energy and moisture balances for the internal space of the building are formulated, the set of outer climate components (here climate of the German city Dresden 1997, table 1) has been completed. The columns in the table 1 mean: 0-Number of hours, 1-Temperature in °C, 2-Relative humidity in %, 3-Diffuse radiation in W/m², 4-Direct radiation in W/m², 5-Precipitation in mm/h, 6-Wind velocity in m/s, 7-Wind direction in °. The temperature and relative humidity can be used directly. The direct and diffuse short wave radiation on the arbitrary outside surface have to calculate with all relevant angles (solar altitude, orientation of building, self shading). The long wave radiation results by means of the direct and diffuse shortwave radiation (cloud coverage) and the relative humidity.

Table 1. Outdoor climate (8760 hourly values) of Dresden, measurement 1997, extraction 4944h to 4959h (July) values in the MATHCAD format.

KDr =

	0	1	2	3	4	5	6	7
4944	4.944·10 ⁻³	15.8	96.01	0	0	0	2.5	288.2
4945	4.945·10 ⁻³	15.68	96.01	0	0	0	2.9	291.94
4946	4.946·10 ⁻³	15.55	96.02	0	0	0	3	289.96
4947	4.947·10 ⁻³	15.5	95.82	0	0	0	3.3	291.06
4948	4.948·10 ⁻³	15.57	94.01	0	0	0	3.7	288.86
4949	4.949·10 ⁻³	15.52	93.33	0	0	0	3.2	297.99
4950	4.95·10 ⁻³	15.23	93.74	1.12	3.13	0	3.6	289.96
4951	4.951·10 ⁻³	15.05	94.3	3.2	25.02	0	4.5	287.54
4952	4.952·10 ⁻³	15.09	93.9	3.74	31.64	0	4.6	293.92
4953	4.953·10 ⁻³	15.18	94.3	0.6	76.99	13	4.1	290.18
4954	4.954·10 ⁻³	16.06	90.14	8.48	125.1	0	5.2	290.18
4955	4.955·10 ⁻³	16.78	81.51	20.04	142.3	0	5.9	282.92
4956	4.956·10 ⁻³	17.38	77.88	16.88	123.8	0	4.7	290.29
4957	4.957·10 ⁻³	18.56	71.3	40.43	251.2	0	4.7	281.6
4958	4.958·10 ⁻³	20.18	62.19	82.21	304.6	0	4.4	275.55
4959	4.959·10 ⁻³	19.8	59.88	38.16	213.6	0	7.1	280.17

For the driving rain on the vertical building parts has been developed an own model [1] by means of the column 5 to 7 and the orientation of the building. For the calculation of all hourly values has been written the C++ **program CLIG (climatic generator)** [3]. Fig. 1 shows the input mask with minicharts of thermic results. Figure 2 illustrates any thermic climatic values for Dresden between April 23th and 26th 1997. The green graph in Fig. 2 (e.g. shortwave radiation on the East wall) shows in the morning a high value (direct and diffuse radiation) and in the afternoon a low level (diffuse radiation only in consequence of the self shading effect).

Fig. 1. CLIG Input mask with minicharts of thermal results.

Fig. 2. Temperature, relative humidity (left coordinate axis), whole short wave radiation shortwave radiation on the East wall and long wave radiation (right coordinate axis), Dresden from April 23th to 26th.

2 Modelling of the energy balances of the indoor room

The first version of the model and program has been described in [2]. Fig. 3 illustrates the thermic balance system of equations for the calculation of the outer surface temperature, the inner surface temperature and the indoor air temperature.

Fig. 3. Energy balances of the interior of the house.

Energy balance of the outer surfaces

$$S_w = T'_w \cdot (\theta_{oe} - \theta_{oi}) + \ddot{U}_e \cdot (\theta_{oe} - \theta_e) + C_e \cdot \frac{d\theta_{oe}}{dt} \tag{1}$$

Energy balance of the indoor air volume, J/2 indoor heat sources versus convection

$$\dot{Q} = (L + T_F) \cdot (\theta_e - \theta_i) + \ddot{U}_i \cdot (\theta_{oi} - \theta_i) + \frac{J}{2} \tag{2}$$

Energy balance of the inner surfaces, J/2 indoor heat sources versus radiation

$$C_i \cdot \frac{d\theta_{oi,j}}{dt} = \Psi_F + \Psi_W \cdot (\theta_{oe} - \theta_{oi,j}) + C_i \cdot (\theta_{oi} - \theta_{oi,j}) + \frac{\Psi_i}{2} \quad (3)$$

The inner surface temperature of the time steps (one hour) $j = 1, 2, \dots, 8760$ is given by the solution (4) of the simple differential equation system (1) to (3)

$$\theta_{oi,j+1} = \theta_{oi,j} + (\theta_{oiLIM,j} - \theta_{oi,j}) \cdot (1 - \exp(-\beta_j \cdot t)) \quad (4)$$

If the temperature is known at the time step j , the temperature at the time step $j+1$ can be calculated by a simple exponential time function. The heat capacity C_L of the room air is approximately zero. The heat capacity of the inner storage mass C_i and of the outside storage mass C_e is depending on the penetration depth or the penetration time of the thermic signal (λ thermal conductivity, c specific heat capacity, ρ density, A_O inner or outer surface, t_{sp} penetration time {e.g. in Central Europe approximately the weather change time from 10 days})

$$C = \frac{1}{2} \cdot \sqrt{\frac{t_{sp}}{\pi}} \cdot \lambda \cdot \rho \cdot c \cdot A_o \quad (5)$$

The heat transport terms are given by: $T_W' = U_W \cdot A_W$ (transmission for walls and roofs without transition coefficients), $T_F = U_F \cdot A_F$ (transmission for the windows including the transition coefficients), $S_W = a \cdot G \cdot A_{We}$ (indirect radiation transport through the walls and roofs, G whole radiation loading, a absorption coefficient), $S_F = f_R \cdot z \cdot g \cdot G \cdot A_F$ (direct radiation through the windows, f frame factor, z shadowing factor, g permeability of glass, G whole radiation loading), $\ddot{U}_i = h_i \cdot A_{Wi}$, $\ddot{U}_e = h_e \cdot A_{We}$ (transition on the inner and outer surfaces, h transition coefficient). L means the heat transmission value by the ventilation rate n_L : $L = \rho_L \cdot c_{pL} \cdot n_L \cdot V_L$. The dimensional units of these items are: θ in $^{\circ}\text{C}$, T_W' , $\ddot{U}_i$, $\ddot{U}_e$, T_F , L in W/K , C in Ws/K , S in W , J in W .

The limit surface temperature $\theta_{oiLIM,j}$ and the written out indoor air temperature $\theta_{iLIM,j}$ in (9) contain only the transport terms, the radiation gains and the inner heat sources. The time coefficient β_j contains the transport terms and the heat capacities of the building parts (equations (6) to (8)).

$$\beta_j = \frac{-E_j}{2} - \sqrt{\left(\frac{E_j}{2}\right)^2 + B_j} \quad (6)$$

$$E_j = \frac{\ddot{U}_i}{C_i \cdot (L_j + T_F)} \cdot \left(\frac{I}{\ddot{U}_i} + \frac{I}{L_j + T_F} \right) - \frac{T'_W + \ddot{U}_e}{C_e} - \frac{T'_W + \ddot{U}_i}{C_i} \quad (7)$$

$$B_j = \frac{T'_W + \ddot{U}_e}{C_i \cdot C_e} \cdot \left(\frac{I}{\ddot{U}_i} + \frac{I}{L_j + T_F} + \frac{I}{T'_W + \ddot{U}_e} \right) \quad (8)$$

Finally the indoor air temperature for each time step (1h) from j to $j+1$ is given by equation (9). The total number of time steps is 8760 h for a year.

$$\theta_{i,j+1} = \theta_{i,j} + \left[\begin{aligned} &\theta_{e,j} - \theta_{i,j} + \\ &\frac{\left(\frac{S_{Fj}}{\ddot{U}_e} + \frac{S_{Fj}}{T'_w} + \frac{S_{Wj}}{\ddot{U}_e} \right)}{(L_j + T_F)} \\ &\frac{\frac{I}{\ddot{U}_e} + \frac{I}{T'_w} + \frac{I}{\ddot{U}_i} + \frac{I}{L_j + T_F}}{\frac{\left(\frac{I}{\ddot{U}_e} + \frac{I}{T'_w} \right)}{(L_j + T_F)} \cdot \frac{J_j}{2} + \frac{\frac{I}{\ddot{U}_e} + \frac{I}{T'_w} + \frac{I}{\ddot{U}_i} + \frac{I}{L_j + T_F}}{\left(I + \frac{\ddot{U}_i}{L_j + T_F + \ddot{U}_i} \right) + \frac{\frac{J_j}{2}}{L_j + \ddot{U}_i + T_F}} \end{aligned} \right] \cdot (1 - \exp(-\beta_j \cdot t)) \quad (9)$$

The solution (9) for the indoor air temperature contains all heat transport coefficients T , $\ddot{U}$, L , the solar radiation values S , the indoor heat sources J and in β_j the heat storage coefficients C in logical and clear manner. The heating power J can be given manually or in dependence on the outside or inside climate. The same applies to the ventilation rate n and the shading z . The intensity of the internal heat sources bases on the use of the internal space.

3 Modelling of the moisture balances of the indoor room

The moisture balances can be formulated like the heat energy balances. The driving potential is now the water vapour pressure. The moisture storage terms depend on the hygroscopicity ($w_h = dw/d\phi$ slope of the hygroscopic isotherm) and the water vapour diffusion (μ -value) of the materials of the inner surfaces. The model for the determination of the room temperature can be transferred analogously to the calculation of the water vapor pressure or the relative humidity. The moisture model is comparatively easy, because no moisture is transported by transmission through the comprehensive construction (unless rain penetrates the building parts) and there is no "humidity radiation". The important variables (Fig. 4) are: actual vapour pressure p_{De} , saturation vapour pressure p_{se} and relative humidity ϕ_e for the outside and p_{Di} , p_{si} and ϕ_j for the inside, the moisture storage stream of the room air dm_{sPL}/dt , of the walls or of the furnishings dm_{spi}/dt , the airborne moisture flow dm_L/dt , the moisture transfer flow $dm_{\ddot{U}i}/dt$ and the moisture flow of the inner sources dm_{QU}/dt .

$$\frac{d}{dt} m_{sPL} = C_{LF} \cdot \frac{d}{dt} p_i \quad \text{Moisture flow stored from the room air} \quad (10)$$

$$\frac{d}{dt} m_L = \frac{V_L \cdot n_L}{R_D} \cdot \left(\frac{p_e}{T_e} - \frac{p_i}{T_i} \right) \text{ Moisture flow transmitted by ventilation rate } n_L \quad (12)$$

$$\frac{d}{dt}m_{\dot{v}_i} = \ddot{U}_{iF} \cdot (p_{oi} - p_i) \quad \text{Moisture flow delivered and recorded from walls} \quad (13)$$

$$\frac{d}{dt}m_{QU} = m_{pV} \cdot V_L \quad \text{Moisture flow submitted from internal moisture sources} \quad (14)$$

Fig. 4. Moisture balances of the interior of the house.

The moisture flow model (15) to (17) can be formulated analogously the energy flow model in section 2 (equations (1) to (3)). The moisture flow through the wall can be neglected, because the hygric transmission term is approximately zero.

$$\frac{d}{dt}m_T = 0 \quad (15)$$

Indoor air humidity balance

$$C_{LF} \cdot \frac{dp_i}{dt} = \frac{V_L n_L}{R_D} \cdot \left(\frac{p_e}{T_e} - \frac{p_i}{T_i} \right) + \ddot{U}_{iF} \cdot (p_{oi} - p_i) + m_{plV} \cdot V_L \quad (16)$$

Interior surface moisture balance

$$C_{iF} \cdot \frac{dp_{oi}}{dt} = \ddot{U}_{iF} \cdot (p_{oi} - p_i) \quad (17)$$

Instead of the temperature the water vapour pressure acts as the driving potential. The moisture balance equation on the outer surface is not relevant for the indoor air humidity and therefore it can be omitted (15). However, the moisture storage capacity of the indoor air C_{LF} in kg/Pa in the moisture balance equation for room air (16) must be considered. It follows from the gas equation, $R_D=462\text{Ws/kgK}$.

$$C_{LF} = \frac{V_L}{R_D \cdot T_i} \quad (18)$$

Analogous to the specific heat ventilation flows L are the specific (now related to the vapour pressure) ventilation moisture flows L_{Fi} and L_{Fe} in (19)

$$L_{Fi} = \frac{V_L \cdot n_L}{R_D \cdot T_i}, \quad L_{Fe} = \frac{V_L \cdot n_L}{R_D \cdot T_e} \quad (19a, 19b)$$

The moisture transfer value in (16) and (17) from room air /inner surfaces in kg/sPa is given by (20) (h_c thermic transition coefficient by convection):

$$\ddot{U}_{iF} = 7,9 \cdot 10^{-9} \frac{\text{kg}}{\text{Pa}} \frac{\text{K}}{\text{Ws}} \cdot h_c \cdot A_{oi} \quad (20)$$

The humidity flow of the sources $dm_{Qu}/dtdV = m_{ptV}$ in $\text{kg}/\text{m}^3 \text{ h}$ in (16) is released completely (not just half like in (2)) into the air. Moisture is not transferred by radiation. In the moisture balance equations the terms T and S are deleted. The moisture storage in the enclosure surface area or furnishings C_{iF} in kg/Pa is depending on the penetration depth of the hygric signal (t_{sp} the storage time, $\delta_L = 1.85 \cdot 10^{-10} \text{ s}$ vapour conductivity in air), compare the thermic storage capacity equation (5)

$$C_{iF} = \frac{I}{2} \cdot \sqrt{\frac{t_{sp}}{\pi}} \cdot \sqrt{\frac{\delta_L}{\mu}} \cdot \rho_w \cdot \frac{w_h}{p_s} \cdot A_{oi} \quad (21)$$

The balance equations (17) are inserted into the equation (16), which leads to a simple differential equation for calculating the time course of the water vapour pressure p_{oi} on the inner surface and later for the room air p_i . The solution for the $(j+1)$ -st (selected here again a total of 8760 hours time steps for a year) period is (compare (9)).

$$p_{oi,j+1} = p_{oi,j} + \left(p_{oi,LIM,j} - p_{oi,j} \right) \cdot \left(1 - \exp(-\beta_{Fj} \cdot t) \right) \quad (22)$$

Herein means $p_{oi,LIM,j}$, the water vapour pressure at the surface after an infinitely long time, $p_{oi,j}$ is the pressure at the beginning of the j -th time step, $p_{oi,j+1}$ is the pressure at the end of the j -th time step and β_{Fj} is the time constant for the humidity adjustment within the j -th time step.

$$p_{oi,LIM,j} = p_{e,j} + \frac{m_{ptV} \cdot R_D \cdot T_i}{n_{Lj}} \quad (23)$$

$$\beta_{Fj} = \frac{I}{C_{iF}} \cdot \left[\frac{\frac{I}{R_D \cdot T_i} + \frac{I}{V_L \cdot n_{Lj}}}{\ddot{U}_{iF}} \right] \quad (24)$$

Equation (24) corresponds to equation (6) in chapter 2. To determine the partial pressure of water vapour of the outside air at the time j or time $j+1$ and the saturation

pressure must be calculated depending on the outside air temperature (see column 2 in table 1)

$$p_{se,j} = 610,5 \cdot \left(e^{\frac{17,26\theta_{e,j}}{273,3+\theta_{e,j}}} \cdot \Phi(\theta_{e,j}) + e^{\frac{21,87\theta_{e,j}}{265,5+\theta_{e,j}}} \cdot \Phi(-\theta_{e,j} - 10^{-6}) \right) \quad (25)$$

The step function Φ in (21) is 1 for positive arguments and 0 for negative arguments. With the measured values of the outside relative humidity ϕ_{ej} (see column 3 in table 1) follow the vapour pressure

$$p_{e,j} = \phi_{e,j} \cdot p_{se,j} \quad (26)$$

Finally the water vapour pressure of the room air is given by:

$$p_{i,j+1} = \frac{p_{o,j+1} \cdot \dot{U}_{iF} + p_{o,j+1} \cdot \frac{V_L \cdot n_{Lj}}{R_D \cdot T_i} \cdot 3600}{\frac{V_L \cdot n_{Lj}}{R_D \cdot T_i} \cdot 3600 + \dot{U}_{iF}} \quad (27)$$

From the water vapour pressure (27) and the saturation pressure (25) in the room the second major component of indoor climate, the inside relative humidity, at the time $j+1$ follows

$$\phi_{i,j+1} = \frac{p_{i,j+1}}{p_{si,j+1}} \quad (28)$$

From the values for the air humidity at time j , the values can be calculated by a simple loop for the time $j+1$. No iteration is required. The moisture sources m_{ptV} can be given manually or in dependence on the outside or inside climate. The same applies to the ventilation rate n . The intensity of the internal moisture sources bases on the use of the internal space.

4 CLIMT Example: „Golden hall“ in Nürnberg

The equations (9) and (22) with (28) have been written ad first in MATHCAD and than in C++ and they form the central part of the **CLIMT program**. For the room geometry (compare Fig. 5) and the all room using parameters are to design simple input masks. The outside climate (in this chapter the measured file Nürnberg 2015) will be supplied by the **CLIG program**. The **program CLIMT** is user friendly and suitable for the common professional use. Up to now following test houses have been investigated: a so called floating house in South Brandenburg from the BTU in Cottbus (built 2008) [1], a library archive in Magdeburg (built 2014) [1] and the “Golden hall” below the “Zeppelin-terrace” (Figs. 6 and 7, in renovation since 2015 by the Hochbauamt Nürnberg) [4].

Fig. 5. Example for the **CLIMT** input mask (detailed room structure), mini grafik of temperature (red) and relative humidity (green) and an overview of the other input masks (CAD input, ventilation, heating, shadow of windows, thermic sources, hygric sources).

Fig. 6. Ruin of the Zeppelintribüne Nürnberg. **Fig. 7.** „Golden hall “ below the terrace length 36.6m. width 8.6m, heigth 7m.

Fig. 8. Indoor air temperature 2015, measured (red), calculated by **CLIMT** (black) in the Golden hall.

Fig. 9. Indoor air relative humidity in 2015, measured (blue), calculated by **CLIMT** (black).

The measured and the calculated values for the actual situation (measured climatic file Nürnberg 2015, without visitors, without heating system) agree very well. In the future this “controversial monument” should be used for a limited number of visitors. For these purposes a photovoltaic equipment completed by a simple electrical radiation heating system (panel radiators a 600W) will be installed..

The temperature during the wintertime should be higher than 8°C. The situation during the summer is not critical because the monument is a very heavy building. The detailed legend of the Fig. 10 (**screen chart of the CLIMT program**) shows the indoor climate under the proposed conditions. By way of comparison all temperature graphs in the mentioned test houses have been calculated also by the TRNSYS program [5] with a good accordance. However the moisture tool in TRNSYS is physical incorrect and therefore it has not been used.

Fig. 10. Indoor climate in the „Golden hall“ in Nürnberg under condition of use prognosticated by CLIMT. Relative humidity in % (magenta), temperature in °C (black), left coordinate axis. Maximum temperature 25.4°C, minimum temperature 8.6°C, outdoor climate Nürnberg 2015. Conditions of use: 40 people a 100W for four times one hour daily, light intensity during this time 1600 W, photovoltaic heating system (monthly mean value as step function, active only during the day, excluding June to August), additional electrical heating power from 9am. to 6pm by day (January 6kW, February 4kW) and from 3am to 9am by night. (January and February 3kW), (blue), right coordinate axis, whole additional electrical heating energy 3336 Wh., ventilation rate November to February 0.05/h, March to October 0.2h/h. The mask shows the thermic threshold values in February.

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