Data article

Title: *Methodology to develop an excel tool aiming at estimating the heating energy demands of the AHUs serving classrooms during an entire scholar year: i.e. the integration of the computed heat transfer rate over the considered period of time*

Authors: Luísa Dias Pereira[a], Francisco Lamas[b], Manuel Gameiro da Silva[a],

Affiliations: a – ADAI, LAETA – Department of Mechanical Engineering, University of Coimbra, Rua Luis Reis Santos, University of Coimbra, 3030-789 Coimbra, Portugal; b – University of Aveiro, Portugal.

Contact email: luisa.pereira@uc.pt

Abstract

In many secondary schools in Portugal, indoor air quality is currently assured by mechanical ventilation. In some cases, Air Handling Units (AHUs) are used to supply fresh air at the rooms conditions. Once in the classrooms, thermal loads are suppressed by terminal units, e.g. hot water radiators (used for heating conditions, at 20 ºC). Some heating capacity is also due to a differential temperature between the outdoor air entering the AHU and the supply air into the room.

Based upon these considerations and specifically for air-supplying at room conditions, the authors developed an excel tool, aiming at estimating the heating energy demands of the AHUs serving classrooms during an entire scholar year, i.e. the integration of the computed heating transfer rate over the considered period of time. This working file includes the integration of an 'Energy Plus' weather file that may vary according to the building site. Therefore, the energy estimations account on the supplied air temperature differential, between the outside air temperature and the desired temperature of the supplied air during the occupancy period.

A detailed description of the methodology developed to build this tool – which is mostly rooted on The 2013 ASHRAE Handbook of Fundamentals (Chapter 1) [1] – *is next presented.*

Specifications

Subject area	*Engineering*
More specific subject area	*Mechanical engineering, Building systems*
Type of data	*Mathematical formulae, table, text file*
How data was acquired	*Consulting the cited reference*
Data format	*Raw, analysed*
Experimental factors	*N/A*
Experimental features	*It is presented a detailed description of a methodology [rooted on The 2013 ASHRAE Handbook of Fundamentals (Chapter 1)] that allowed developing a tool to estimate the heating energy demands of AHUs serving classrooms.*
Data source location	*N/A*
Data accessibility	*Data are within this article*

Nomenclature

c_p	specific heat capacity of moist air [kJ/(kg$_{da}$.K)]
$c_{p_{da}}$	specific heat capacity of dry air [kJ/(kg$_{da}$.K)]
c_{p_w}	specific heat capacity of water vapor [kJ/(kg$_w$.K)]
h	specific enthalpy of moist air [kJ/kg$_{da}$]
h_{coil}	specific enthalpy of moist air at coil conditions [kJ/kg$_{da}$]
h_{sup}	specific enthalpy of moist air at supplying conditions [kJ/kg$_{da}$]
h_w	specific enthalpy of vaporization of ice or water [kJ/kg$_w$]
$h_{w,0°C}$	specific enthalpy of water vapor at 0°C and 101.325 kPa [kJ/kg$_w$]
M_{da}	molar mass of dry air [g/mol]
M_w	molar mass of water vapor [g/mol]
p_{ws}	saturation pressure [Pa]
$\dot{q}_{lat}$	latent heat load [kW]
$\dot{q}_{dehum}$	dehumidification load [kW]
$\dot{q}_{sen}$	sensible heat load [kW]
$\mathcal{R}$	universal gas constant [kJ/(kmol.K)], value of 8.314472 kJ/(kmol.K)
R_{da}	gas constant for dry air [J/(kg$_{da}$.K)]
R_w	gas constant for water vapor [J/(kg$_w$.K)]
t	dry air temperature [°C]
T	dry air absolute temperature [K]
t_{out}	dry air temperature at outdoor conditions [°C]
t_{sup}	dry air temperature at supplying conditions [°C]
v	specific volume [m^3/kg$_{da}$]
$\dot{V}$	airflow rate [m^3/h]
W	humidity ratio [kg$_w$/kg$_{da}$]
W_{coil}	humidity ratio at coil conditions [kg$_w$/kg$_{da}$]
W_{out}	humidity ratio at outdoor conditions [kg$_w$/kg$_{da}$]
W_s	humidity ratio at saturation [kg$_w$/kg$_{da}$]
W_{sup}	humidity ratio at supplying conditions [kg$_w$/kg$_{da}$]
Δ	variation of (variable) [variable units]
ρ	density [kg$_{da}$/m^3]
ϕ	relative humidity [%]

Methodology

Psychrometrics and thermophysical overview

Atmospheric air is a mixture of several gaseous components, water vapor and some contaminants. The portion of atmospheric air exempt from water vapor and contaminants, is denominated by dry air, whose composition is relatively constant, varying slightly with time, geographic location and altitude [1]. An approximate composition of dry air is shown in **Table 1**. According to *The 2013 ASHRAE Handbook of Fundamentals* [1], supported in former research results, carbon dioxide concentration is increasing at an annual rate of 0.00019 %, offset by the decrease of oxygen, at the same rate. These considerations were taken into account to forecast both oxygen and carbon dioxide percentage compositions by volume for the present year, 2015, matching the gas constant for dry air:

$$R_{da} = \frac{\mathcal{R}}{M_{da}} = 8314.472/28.966 = 287.042 \text{ J/(kg}_{da}\text{.K)} \quad \text{(A.1)}$$

and the gas constant for water vapor (with a molar mass of approximately 18.015 g/mol), linking element to the dry air for the formation of moist air:

$$R_w = \frac{\mathcal{R}}{M_w} = 8314.472/18.015 = 461.524 \text{ J/(kg}_w\text{.K)} \quad \text{(A.2)}$$

where:

R_{da} - gas constant for dry air [J/(kg$_{da}$.K)]
R_w - gas constant for water vapor [J/(kg$_w$.K)]
$\mathcal{R}$ - universal gas constant [J/(kmol.K)]
M_{da} - molar mass of dry air [g/mol]

M_w - molar mass of water vapor [g/mol]

Table 1 –Approximate dry air composition, in percentage composition by volume and molar mass, adapted from [1].

Gaseous component	Chemical composition	Percentage composition by volume [%]	Molar mass [g/mol]
Nitrogen	N_2	78.084	28.014
Oxygen	O_2	20.9381 (forecast)	31.999
Argon	Ar	0.934	39.948
Carbon dioxide	CO_2	0.0409 (forecast)	44.010
Neon	Ne	0.001818	20.180
Helium	He	0.000524	4.003
Methane	CH_4	0.00015	16.043
Sulfur dioxide	SO_2	0 to 0.0001 (considered 0.0001)	64.059
Hydrogen	H	0.00005	1.008
Krypton	Kr		83.798
Xenon	Xe	0.0002	131.293
Ozone	O_3		47.998
Total (dry air)	**-**	**≈100.000**	**28.996**

For the determination of the moist air properties, the water vapor saturation pressure is required. The methodology followed by [1] presents two formulas developed by Hyland and Wexler, one, Equation (A.3), for the saturation pressure over ice (-100 °C $\leq t \leq$ 0 °C), and the other, Equation (A.4), for the saturation pressure over liquid water (0 °C $\leq t \leq$ 200 °C):

$$\ln p_{ws} = C_1/T + C_2+C_3T+C_4T^2+C_5T^3+C_6T^4+C_7\ln T \quad \text{(A.3)}$$

$$\ln p_{ws} = C_8/T + C_9+C_{10}T+C_{11}T^2+C_{12}T^3+C_{13}\ln T \quad \text{(A.4)}$$

where:

p_{ws} - saturation pressure [Pa]
T - dry air absolute temperature [K], $T = 273.15 + t$, where t [°C]
C_1 - constant, $-5.6745359 \times 10^{+03}$
C_2 - constant, $6.3925247 \times 10^{+00}$
C_3 - constant, $-9.6778430 \times 10^{-03}$
C_4 - constant, $6.2215701 \times 10^{-07}$
C_5 - constant, $2.0747825 \times 10^{-09}$
C_6 - constant, $-9.4840240 \times 10^{-13}$
C_7 - constant, $4.1635019 \times 10^{+00}$
C_8 - constant, $-5.8002206 \times 10^{+03}$
C_9 - constant, $1.3914993 \times 10^{+00}$
C_{10} - constant, $-4.8640239 \times 10^{-02}$
C_{11} - constant, $4.1764768 \times 10^{-05}$
C_{12} - constant, $-1.4452093 \times 10^{-08}$
C_{13} - constant, $6.5459673 \times 10^{+00}$

From the mass of water vapor to the mass of dry air ratio (mole fraction ratio multiplied by the ratio of molecular masses) and considering moist air as a mixture of independent perfect gases (dry air and water vapor), where the ideal gas law can be applied to both, individually, and to the resulting mixture, through the Dalton's Law of partial pressure, the humidity ratio at saturation can be achieved by:

$$W_s = (R_{da}/R_w)\frac{p_{ws}}{p-p_{ws}} \quad [kg_w/kg_{da}] \quad \text{(A.5)}$$

where:

W_s - humidity ratio at saturation [kg_w/kg_{da}]
R_{da} - gas constant for dry air [$J/(kg_{da}.K)$]
R_w - gas constant for water vapor [$J/(kg_w.K)$]
p_{ws} - saturation pressure [Pa]
p - barometric pressure [Pa]

Relating the degree of saturation (ratio of air humidity ratio to the saturation humidity ratio, at the same temperature and pressure), the relative humidity (ratio of the mole fraction of water vapor in a sample of moist air to the mole fraction of water vapor in an air sample saturated, at the same temperature and pressure) and the humidity ratio at saturation, Equation (A.6), the humidity ratio can be achieved by:

$$W = W_s \frac{\phi}{1+(1-\phi)W_s/(R_{da}/R_w)} \qquad [kg_w/kg_{da}] \qquad (A.6)$$

where:

W - humidity ratio [kg_w/kg_{da}]
W_s - humidity ratio at saturation [kg_w/kg_{da}]
ϕ - relative humidity [%]
R_{da} - gas constant for dry air [$J/(kg_{da}.K)$]
R_w - gas constant for water vapor [$J/(kg_w.K)$]
p_{ws} - saturation pressure [Pa]
p - barometric pressure [Pa]

Once known the humidity ratio, other psychrometric properties of moist air can be estimated, for specific temperature and pressure conditions. The specific volume (Equation (A.7)), density (Equation (A.8)), specific enthalpy (Equation (A.9)) and specific heat capacity (Equation (A.10)) can be obtained from aforementioned properties and formulas, and correlation between themselves:

$$v = \frac{R_{da}(t+273.15)(1+W/(R_{da}/R_w))}{p} \qquad [m^3/kg_{da}] \qquad (A.7)$$

$$\rho = (1/v)(1+W) \qquad [kg_{da}/m^3] \qquad (A.8)$$

$$h = c_{p_{da}} t + W\left(h_{W,0°C} + c_{p_w} t\right) \qquad [kJ/kg_{da}] \qquad (A.9)$$

$$c_p = c_{p_{da}} + W c_{p_w} \qquad [kJ/(kg_{da}.K)] \qquad (A.10)$$

where:

v - specific volume [m^3/kg_{da}]
ρ - density [kg_{da}/m^3]
h - specific enthalpy of moist air [kJ/kg_{da}]
c_p - specific heat capacity of moist air [$kJ/(kg_{da}.K)$]
R_{da} - gas constant for dry air [$J/(kg_{da}.K)$]
R_w - gas constant for water vapor [$J/(kg_w.K)$]
W - humidity ratio [kg_w/kg_{da}]
t - dry air temperature [°C]
p - barometric pressure [Pa]
$h_{w,0°C}$ - specific enthalpy of water vapor at 0 °C and 101.325 kPa [kJ/kg_w]
$c_{p_{da}}$ - specific heat capacity of dry air [$kJ/(kg_{da}.K)$]
c_{p_w} - specific heat capacity of water vapor [$kJ/(kg_w.K)$]

[2], in accordance with [1] , presents 2501 kJ/kg_w for $h_{w,0°C}$, but considers temperature-dependent specific heat capacities, for dry air and water vapor, $c_{p_{da}} = 1.0029 + 5.4 \times 10^{-05} t$ [$kJ/(kg_{da}.K)$] and $c_{p_w} = 1.856 + 2.0 \times 10^{-04} t$, [$kJ/(kg_w.K)$], in opposition to 1.006 $kJ/(kg_{da}.K)$ and 1.84 $kJ/(kg_w.K)$ respectively.

Due to the inexistence of a consensual empirical correlation to determine the latent heats of sublimation and vaporization for water, it was used h_w (h_{ig} for ice and h_{fg} for liquid water) directly from the values presented by [1].

Thermal loads

Fresh air is supplied, at (or nearly) room conditions (dry air temperature and eventually humidity), or at certain conditions that will provide the desired thermal-hygrometric set points. These thermal processes are triggered by sensible and, eventually, latent evolutions, *i.e.* energy transfer rates for adjusting the temperature (Equation (A.11)) and moisture content (Equation (A.12)) of the fresh air, from outdoor to indoor (or supply) conditions, respectively. For dehumidification processes and particularly for all-air systems, where supply air temperature and humidity are defined to assure the room conditions, an additional evolution is demanded (Equation (A.13)). These evolutions can be expressed by:

$$\dot{q}_{sen} = \frac{\rho \dot{V} c_p}{3600} \Delta t \qquad \text{[kW]} \qquad \text{(A.11)}$$

$$\dot{q}_{lat} = \left(\frac{\rho \dot{V}}{3600} \Delta W\right) h_w \qquad \text{[kW]} \qquad \text{(A.12)}$$

$$\dot{q}_{dehum} = \left(\frac{\rho \dot{V}}{3600} \Delta W\right) \frac{\Delta h'}{\Delta W'} \qquad \text{[kW]} \qquad \text{(A.13)}$$

where:

$\dot{q}_{sen}$ - sensible heat load [kW]
$\dot{q}_{lat}$ - latent heat load [kW]
- dehumidification load [kW]
Δt - dry air temperature variation [°C], $(t_{sup} - t_{out})$ for sensible heating and $(t_{out} - t_{sup})$ for sensible cooling processes
ΔW - humidity ratio variation [kg_w/kg_{da}], $(W_{sup} - W_{out})$ for latent heating and $(W_{out} - W_{sup})$ for latent cooling processes
$\Delta W'$ - humidity ratio variation [kg_w/kg_{da}], $(W_{sup} - W_{coil})$ for dehumidification, considering supplying and coil conditions
$\Delta h'$ - specific enthalpy variation [kJ/kg_{da}], $(h_{sup} - h_{coil})$ for dehumidification, considering supplying and coil conditions
ρ - density volume [kg_{da}/m^3]
c_p - specific heat capacity of moist air [$kJ/(kg_{da}.K)$]
h_w - specific enthalpy of vaporization of ice or water [kJ/kg_w]
$\dot{V}$ - airflow rate [m^3/h]

Acknowledgements

The presented work is part of a wider research project, entitled Energy Efficient Schools (*Escolas Energeticamente Eficientes, 3Es*), granted by Teixeira Duarte on the framework of the Portuguese Program of R&D Projects associated to Large Public Tenders. The authors are thankful to Parque Escolar E.P.E. for the provision of the database on the Portuguese secondary schools. The presented work is framed under the Energy for Sustainability Initiative of the University of Coimbra and LAETA (Associated Laboratory for Energy, Transports and Aeronautics) Project Pest E/EME/LA0022/2011 and was supported by the Foundation for Science and Technology under grant SFRH/BD/77105/2011.

References

[1] ASHRAE, *ASHRAE Handbook - Fundamentals 2013*. Atlanta: American Society of Heating Refrigerating and Air-Conditioning Engineers, 2013.

[2] Z. K. Morvay and D. D. Gvozdenac, “Part III: FUNDAMENTALS FOR ANALYSIS AND CALCULATION OF ENERGY AND ENVIRONMENTAL PERFORMANCE,” in *Applied Industrial Energy and Environmental Management*, Wiley-IEEE., John Wiley & Sons, Inc., 2008, p. 456.