

# VENTILATION HEAT LOSS IN A MULTIFAMILY BUILDING UNDER VARYING AIR DENSITY

Piotr MICHALAK<sup>1\*</sup>

<sup>1\*</sup> Faculty of Mechanical Engineering and Robotics, Department of Power Systems and Environmental Protection Facilities, AGH University of Science and Technology, Mickiewicza 30, 30-059 Kraków, Poland, e-mail: pmichal@agh.edu.pl

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**Abstract:** Standards related to calculation methods used in building energy performance simulation tools usually impose constant volumetric heat capacity of air. However, this simplification may result in errors if the actual conditions differ from the assumptions made. The paper presents the problem of dry air density and specific heat capacity variation and their influence on calculated energy use for space heating in a multifamily building. The monthly calculation method of PN-EN ISO 13790 was used. Simulations were performed in five cities, each in one climatic zone according to PN-EN 12831. Variation of the air density caused by air temperature and elevation resulted in differences in calculated heating demand from -4.5% to 4.5% in relation to that at constant volumetric heat capacity assumed in PN-EN ISO 13790.

**Keywords:** air density, heat capacity of dry air, volumetric heat capacity, ventilation heat loss, EN ISO 13790, monthly method

## 1. INTRODUCTION

Poland is the country with heating dominated climate [1-3]. Thus, energy use for space heating has significant share in total energy consumption in Polish buildings. One of the elements influencing heating demand is the ventilation (including ventilation and infiltration) heat loss [4-6]. Its importance increases with new standards [7], both in low-energy and passive [8] as well as in thermally refurbished objects [9]. This is so, because the main task of ventilation is to provide fresh air and to remove used air independently on the energy standard of a building.

Mathematical models applied in simulation tools used in energy auditing, design or certification of buildings commonly assume constant air density and specific heat capacity. But varying outdoor conditions cause these parameters to change.

This paper presents an assessment of the impact of the air density on the ventilation heat loss and resulting heating demand of a multifamily residential building in five cities, each in different Polish climatic zone. Calculations were performed using the monthly method of PN-EN ISO 13790 [10]. The ventilation heat loss was determined at constant volumetric heat capacity of

air of  $1200 \text{ J/m}^3\cdot\text{K}$ , imposed in that standard, and comparatively at monthly outdoor air temperatures from monthly weather data.

## 2. VOLUMETRIC HEAT CAPACITY OF DRY AIR

### 2.1. Introduction

Calculation methods of PN-EN ISO 13790 to assess thermal performance of buildings don't take into account humidification or dehumidification processes. Hence, basic properties of dry air are described briefly in the following paragraphs.

### 2.2. Air density

Within the air temperature and atmospheric pressure variation met in climatic conditions of Europe it is sufficient to treat atmospheric air as ideal gas [11]. Hence, assuming current recommendations [12-14], it can be calculated that the density of dry air at standard conditions ( $T_0 = 273.15 \text{ K}$ ,  $p_0 = 100 \text{ kPa}$ ) is  $\rho_0 = 1.27540 \text{ kg/m}^3$  and varies from  $1.43276 \text{ kg/m}^3$  at  $-30^\circ\text{C}$  to  $1.14918 \text{ kg/m}^3$  at  $+30^\circ\text{C}$ , i.e. decreases by 20%.

Atmospheric pressure has slightly less significant, but still noticeable, impact on air density. At  $0^\circ\text{C}$   $\rho_a$  rises from  $1.21163 \text{ kg/m}^3$  at  $950 \text{ hPa}$  to  $1.33917 \text{ kg/m}^3$  at  $1050 \text{ hPa}$ , i.e. by 11% (Fig. 1).

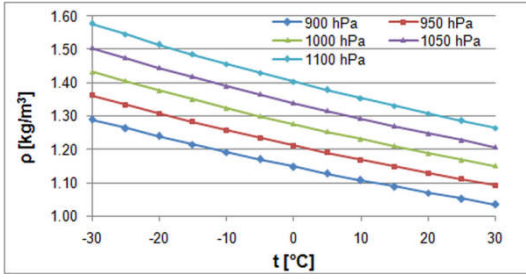


Fig. 1. Air density for different temperatures and pressures

If only temperature measurements are available, the air density at the known elevation can be calculated from the barometric formula [15, 16] at constant temperature (isothermal atmosphere):

$$\rho_{a,h} = \rho_0 \cdot \exp(-g \cdot h / R \cdot T_0). \quad (1)$$

As a reference point typically standard conditions are used. From this:

$$\rho_{a,h} = 1.2754 \cdot \exp(-h/7995.29). \quad (2)$$

In such a case the air density depends only on the air temperature (T) on site:

$$\rho_a(T) = \rho_{a,h} \cdot T_0/T. \quad (3)$$

### 2.3. Specific heat capacity

Specific heat capacity of dry air in the temperature range from  $-50^\circ\text{C}$  to  $+50^\circ\text{C}$  at  $p = 100 \text{ kPa}$  changes from  $c_a = 1006.1 \text{ J/kg} \cdot \text{K}$  to  $1007.7 \text{ J/kg} \cdot \text{K}$ , with the minimum of  $1005.7 \text{ J/kg} \cdot \text{K}$  at  $-20^\circ\text{C}$  (Fig. 2).

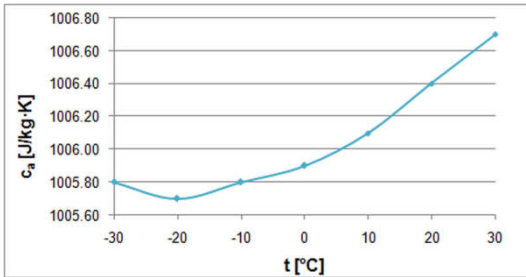


Fig. 2. Specific heat capacity of air at  $p=100 \text{ kPa}$  [17]

Atmospheric pressure has negligible effect on  $c_a$ . For example, at  $0^\circ\text{C}$   $c_a = 1005.9 \text{ J/kg} \cdot \text{K}$  and  $1013.9 \text{ J/kg} \cdot \text{K}$  at  $100 \text{ kPa}$  and  $500 \text{ kPa}$ , respectively. Hence, it seems appropriate to accept  $c_a = 1006 \text{ J/kg} \cdot \text{K}$  for energy simulations of buildings.

## 3. MATERIALS AND METHODS

### 3.1. Monthly method of PN-EN ISO 13790

To assess the thermal performance of buildings in Poland commonly monthly method of PN-EN ISO 13790 is used. This standard has been replaced by PN-EN ISO 52016 recently [18] but the monthly calculation method remained the same in essence [19]. In spite of its simplicity that method provides correct

results [20] and therefore was commonly introduced in national regulations [21].

Thermal balance of a building zone consists of heat losses and heat gains. Heat losses include heat transfer by transmission and by ventilation:

$$Q_{H,ht} = Q_{H,tr} + Q_{H,ve}. \quad (4)$$

Heat gains include solar gains and heat gains from internal sources (occupants, appliances, lighting, tap water and recoverable system thermal losses):

$$Q_{H,gn} = Q_{H,sol} + Q_{H,int}. \quad (5)$$

Calculation of thermal balance over one month takes into account dynamic effects by means of the gain utilization factor for heating. The monthly energy demand for space heating,  $Q_{H,nd}$ , is given by:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}. \quad (6)$$

For a given month the gain utilisation factor for heating,  $\eta_{H,gn}$ , depends on the relation between heat gains and heat losses:

$$\gamma_H = Q_{H,gn}/Q_{H,ht}. \quad (7)$$

If  $\gamma_H > 0$  and  $\gamma_H \neq 1$ :

$$\eta_{H,gn} = \frac{1 - \gamma_H^{\alpha_H}}{1 - \gamma_H^{\alpha_H + 1}}. \quad (8)$$

If  $\gamma_H = 1$ :

$$\eta_{H,gn} = \alpha_H / (\alpha_H + 1), \quad (9)$$

else if  $\gamma_H < 1$ :

$$\eta_{H,gn} = 1/\gamma_H, \quad (10)$$

with:

$$\alpha_H = \alpha_{H,0} + \tau/\tau_{H,0}. \quad (11)$$

In Poland normative default values of  $\alpha_{H,0} = 1 \text{ h}$  and  $\tau_{H,0} = 15 \text{ h}$  are used.

The time constant of a building depends on its internal heat capacity and overall heat transfer coefficients by transmission and by ventilation:

$$\tau = C_m / (H_{tr} + H_{ve}). \quad (12)$$

### 3.2. Ventilation heat loss

For a given thermal zone and time period the total heat loss by ventilation (including air infiltration and ventilation) for heating is calculated from the formula:

$$Q_{H,ve} = H_{ve} \cdot (t_{int,set,H} - t_e) \cdot \Delta\tau, \quad (13)$$

with:

$$H_{ve} = \rho_a \cdot c_a \cdot \dot{v}_{ve}. \quad (14)$$

PN-EN ISO 13790 imposed  $\rho_a \cdot c_a = 1200 \text{ J/m}^3 \cdot \text{K}$ . Assuming  $c_a = 1006 \text{ J/kg} \cdot \text{K}$  (see Section 2.3.) at the pressure of  $100 \text{ kPa}$  the resulting air temperature is

18.9°C. It differs significantly from the average annual outdoor air temperature in Poland [22, 23] of about 8°C, at which fresh air is delivered to interior of buildings via infiltration and ventilation.

### 3.3. Typical meteorological years

Files with typical meteorological years [24] (TMYs) were introduced in Poland in 2008 for building simulations along with the implementation of the Directive on Energy Performance of Buildings (EPBD). They have been prepared for 61 weather stations in Poland in hourly and monthly formats. Monthly data include month number, minimum, maximum and average air temperature (dry bulb), sky temperature, global solar irradiance on a horizontal surface and on sloped surfaces (30°, 45°, 60° and 90°) oriented in eight basic directions (N, NE, E, SE, S, SW, W and NW), the code and the name of the World Meteorological Organization (WMO) station. Hourly data include also day, hour (UTC time), relative humidity, moisture content, wind speed and wind direction. In addition north latitude, east longitude, elevation above sea level, time zone from 0 to east, number of days of meteorological data and the version number of a file are also given.

## 4. CALCULATIONS

### 4.1. Building

To perform necessary simulations a model of a multifamily building was used (Fig. 3).



Fig. 3. View of the building in the Audytor OZC program

It has been built on a rectangular plan of 60 m and 11 m. Thermal resistances of external walls and roof are 4.048 m<sup>2</sup>·K/W and 4.885 m<sup>2</sup>·K/W, respectively.

Its main parameters are shown in Table 1. The design ventilation airflow was set in standard conditions. The thermal capacity of the building,  $C_m$ , was obtained from physical properties of materials using simple method from PN-EN ISO 13786 [25]. Additional data were given in [2].

### 4.2. Test locations

The PN-EN 12831 standard [26] defines five zones for calculation of the design heat load in Poland [27, 28]. Five locations were chosen for further simulations, one in each zone, as listed in Table 2.

Tab. 1. General characteristics of the building

Parameter	Value	Unit
Height above the ground	13.6	m
Total heated area	2991.5	m <sup>2</sup>
Total heated volume	7478.8	m <sup>3</sup>
Heat transfer coefficient by transmission ( $H_{tr}$ )	1324.6	W/K
Internal heat capacity $C_m$	777.8	MJ/K
Internal heat gains density per floor area	4.0	W/m <sup>2</sup>
Design ventilation airflow	7478.8	m <sup>3</sup> /h
External wall area - N	816.0	m <sup>2</sup>
External wall area - S	816.0	m <sup>2</sup>
External wall area - E	149.6	m <sup>2</sup>
External wall area - W	149.6	m <sup>2</sup>
Area of windows - N	172.8	m <sup>2</sup>
Area of windows - S	127.2	m <sup>2</sup>
Area of windows - E	0.0	m <sup>2</sup>
Area of windows - W	0.0	m <sup>2</sup>
Area of the roof	660.0	m <sup>2</sup>

Tab. 2. Chosen test locations

Location	Zone	North latitude	East longitude	Elevation [m]
Koszalin	I	54° 12'	16° 09'	34
Poznań	II	52° 25'	16° 51'	84
Kielce	III	50° 49'	20° 42'	261
Terespol	IV	52° 04'	23° 37'	137
Zakopane	V	49° 18'	19° 58'	857

Applying Eq. (2) air density at standard conditions was calculated for the given elevation. From this, assuming  $c_a = 1006$  J/kg·K and taking annual average air temperatures ( $T$  in Eq. (3)) from weather files, volumetric heat capacity of air was determined. Additionally, the relative percentage error of approximation of calculated volumetric heat capacity of air with that of EN ISO 13790 was calculated.

Tab. 3. Volumetric heat capacity at annual temperature

Location	$t_a$ [°C]	$\rho_{a,h}(t_a)$ [kg/m <sup>3</sup> ]	$\rho_{a,h}(t_a) \cdot c_a$ [J/m <sup>3</sup> ·K]	$\epsilon$ [%]
Koszalin	7.95	1.2700	1241.5	-3.34
Poznań	8.21	1.2621	1232.6	-2.64
Kielce	7.51	1.2344	1208.6	-0.71
Terespol	7.76	1.2537	1226.4	-2.15
Zakopane	5.43	1.1458	1130.2	6.18

Results presented in Table 3 show differences between volumetric heat capacities from two methods. Thus, further calculations of heating demand of the described building in subsequent months of a year were performed in each location.

#### 4.3. Heating demand of the building

Applying the monthly method described in Section 3.1. with proper weather data monthly energy use for space heating of the building was calculated.

Using PN-EN ISO 13790 (first method) at constant  $\rho_a \cdot c_a = 1200 \text{ J/m}^3 \cdot \text{K}$  annual heating demand (Fig. 4) was from 880.41 GJ in Koszalin to 1059.91 GJ in Zakopane. The second method provided results from 923.00 GJ to 1012.43 GJ.

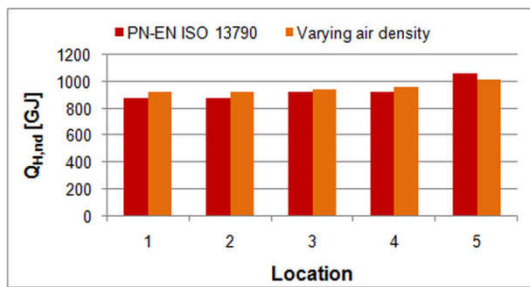


Fig. 4. Calculated annual heating demand

In three cases (1, 2, 4) the new method gave higher values of  $QH,nd$ , by 4.5% on average. Relatively low elevations of these cities didn't significantly reduce the air density. Air temperature in cold half year, from X to III, was lower than  $18.9 \text{ }^\circ\text{C}$  (see Section 3.2.) and finally volumetric heat capacity was higher than  $1200 \text{ J/m}^3 \cdot \text{K}$  resulting in greater ventilation heat loss.

Different situation was observed in locations 3 and 5. The air density calculated in Zakopane (5-th case) at elevation of 857 m (Eq. 2) and  $T_0$  was  $\rho_{a,h} = 1.1458 \text{ kg/m}^3$ , i.e. lower by 10.2% from  $\rho_0$ .

In case of the 3-rd location reduction of air density due to elevation was compensated by lower temperature during heating season. That's why the difference in  $QH$  amounted only 1.5%.

Differences in  $QH,nd$  should be also considered in terms of heating energy consumption per floor area (EA). This is very important indicator from the point of view of energy certification of buildings [29, 30]. The second method resulted in EA from  $4.0 \text{ kWh/m}^2$  higher (Koszalin) to  $4.4 \text{ kWh/m}^2$  lower (Zakopane) than the first one.

## 5. CONCLUSIONS

Varying environmental conditions, especially air temperature and barometric pressure, influence air density and ventilation heat loss in each building.

The monthly calculation method of PN-EN ISO 13790 was used to determine heating demand of a multifamily building in five Polish cities. Air density

variation caused by changes in air temperature and elevation above sea level was described by the ideal gas law and barometric formulas, respectively.

Performed calculations revealed differences in the annual heating demand between two methods and confirmed its dependence on the aforementioned factors. In addition, previous works [2, 31] indicated strong impact of the new PN-EN ISO 52010 standard on calculated solar gains in buildings, comparing to the method used so far, influencing values of heating and cooling demand without any physical changes in the building's structure. This is a premise for a detailed study about the calculation procedures used in the energy calculations of buildings.

## Nomenclature

### Symbols

$g$	- gravitational acceleration, $g = 9.80665 \text{ m/s}^2$
$h$	- elevation above sea level (altitude), m
$t_a$	- mean annual temperature of external air, $^\circ\text{C}$
$t_{int,set,H}$	- internal air temperature for heating, $^\circ\text{C}$
$t$	- external air temperature, $^\circ\text{C}$
$v_{pe}$	- ventilation and infiltration airflow rate, $\text{m}^3/\text{s}$
$C_m$	- internal thermal capacity of the considered building (or zone), J/K
$E_A$	- annual heating energy demand per conditioned unit floor area of a building, $\text{kWh/m}^2$
$H_{tr}$	- heat transfer coefficient by transmission, W/K
$H_{ve}$	- heat transfer coefficient by ventilation, W/K
$Q_{H,gn}$	- total heat gains in a building for heating, kWh
$Q_{H,ht}$	- total heat transfer by transmission and ventilation of a building for heating, kWh
$Q_{H,int}$	- total internal heat gains for heating, kWh
$Q_{H,nd}$	- energy demand for space heating, kWh
$Q_{H,sol}$	- total solar gains for heating, kWh
$Q_{H,tr}$	- total heat transfer by transmission for heating, kWh
$Q_{H,ve}$	- total heat transfer by ventilation and infiltration for heating, kWh
$R$	- universal gas constant, $R = 8.3144598 \text{ J/mol} \cdot \text{K}$
$T$	- external air temperature, K

### Greek letters

$\alpha_H$	- numerical parameter for the heating mode, -
$\alpha_{H,0}$	- reference numerical parameter for the heating mode, $\alpha_{H,0} = 1.0$
$\gamma_H$	- heat gain ratio for heating, -
$\epsilon$	- relative percentage error, %
$\eta_{H,gn}$	- gain utilization factor for heating, -
$\Delta\tau$	- calculation time period, h
$\tau$	- time constant of the building, h
$\tau_{H,0}$	- reference time constant for heating, $\tau_{H,0} = 15 \text{ h}$
$\rho_{a,h}$	- density of dry air at the given elevation $h$ , $\text{kg/m}^3$
$\rho_a(T)$	- air density at the given temperature $T$ , $\text{kg/m}^3$
$\rho_0$	- air density at standard conditions ( $T_0 = 273.15 \text{ K}$ , $p_0 = 100 \text{ kPa}$ ), $\rho_0 = 1.27540 \text{ kg/m}^3$
$\mu$	- molar mass of dry air, $\mu = 28.96546 \text{ g/mol}$

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### Biographical note



Piotr Michalak received Ph.D degree in Energy Machines and Equipment from AGH, Kraków. Since 2009 he has been a researcher in the Department of Power Systems and Environmental Protection Facilities at the AGH. His scientific interests involve thermal dynamics of buildings, utilisation of renewable energy sources, CFD simulations and thermal and flow measurements.

