ENVIRONMENTAL AND CLIMATE TECHNOLOGIES
VIDES UN KLIMATA TEHNOLOĢIJAS

ISSN 1691-5208 2009-5208
10.2478/v10145-009-0008-5

INFLUENCE OF THERMO-DYNAMIC PROPERTIES AND THERMAL INERTIA OF THE BUILDING ENVELOPE ON BUILDING COOLING LOAD

ĒKAS ĀRĒJO NOROBEŽOJOŠO KONSTRUKCIJU SILTUMTEHNISKO ĪPAŠĪBU UN TERMISKĀS INERCES IETEKME UZ ĒKAS AUKSTUMA SLODZI

D. Jaunzems, PhD student, M.Sc.ing.
Institute of Energy Systems and Environment, Riga Technical University
Address: Kronvalda boulv. 1, LV-1010, Riga, Latvia
Phone: +371 67089923, Fax: +371 67089923
e-mail: dzintars.jaunzems@rtu.lv

I. Veidenbergs, professor, Dr. Hab. Sc. Ing.
Institute of Energy Systems and Environment, Riga Technical University
Address: Kronvalda boulv. 1, LV-1010, Riga, Latvia
Phone: +371 67089923, Fax: +371 67089923
e-mail: ivars.veidenbergs@rtu.lv

Keywords*: building envelope, cooling load, thermal inertia, thermal mass, thermo-dynamic properties*

Introduction

Buildings are responsible for about 30 % of total energy consumption of Latvia. Specific heat consumption is 200-225 kWh/m^2 annual, but average annual electric consumption is about 1000-1200 kWh per household. Household sector still have huge potential to improve energy efficiency, thus reduce impact on climate and environment.

Internal heat gains of new building are increasing due to request for comfort and change of behavior of consumers, for that reason cooling load of building is more and more significantly to assume not only in hot regions but also in colder regions, e.g. Latvia and Northern Europe.

Till now in different investigations on energy performance of buildings very often is used calculation models only for steady-state conditions (calculations for season or yearly heat demand etc.), for example, Regulations issued by the Cabinet of Ministers of Republic of Latvia nr. 39 "Calculation method of building energy performance" (confirmed on 13.01.2009). This approach is approved and correct but unfortunately don't show any dynamic processes (thermal inertia, thermal transfer between the internal and external environment etc.) cause applied only for monthly, seasonal or yearly calculations. Hence there was developed hourly cooling load calculation model based on EU standard EN 15255:2007 (has a status of Latvian Standard) and approbated in Latvian conditions.

Accurately calculated hourly cooling load must be taken in consideration choosing suitable cooling equipment and defining installed capacity.The use of thermal mass in a building can reduce peak heating or cooling load, and subsequently building energy consumption, particular when it is integrated with night ventilation. Thermal mass is defined as the thermal materials that can absorb heat, store it and release it later. Thermal mass includes building envelope, furniture, internal walls, etc. Thermal storage capacity of building mass is one of the factors describing the building thermal performance [1]. Influence of thermal inertia on cooling load can be positive, negative or neutral.

Optimal use of building thermal inertia can help: (1) to reduce and delay cooling load peaks, in other words, to stabilize and equalize cooling load curve of building during season; (2) to avoid from large fluctuations of internal temperature based on swings of external temperature, and so, provide better thermal comfort and microclimate for residents and reduce energy consumption for cooling.

Scope of the paper

The paper focuses on phenomena of thermal inertia and thermal mass effect of building envelope, basically in terms of decrement factor and time lag. Evaluation consist of several main stages: (1) Calculation of hourly cooling load and internal temperature of existing building (including collecting and calculation of all data and definition of set-point internal temperature); (2) Study on thermal inertia and thermal mass factors, e.g. the decrement factor, time lag; (3) Investigation of influence due improving thermal inertia, precisely, the equivalent thermal mass area of building on decrement factor and time lag, as well, on cooling load of building for defined conditions.

Due to complexity of the topic, there is assumed some simplifications to reach universalized interconnections.

Reference building

For all calculations and evaluations there was used reference building: a real and typical three-storey residential building in Latvia built in the end of 1960s (see Fig. 1). All data was obtained during energy audit.

Basic data of the reference building: length 24.5 m, width 10.5 m and height 9 m. Windows area (glazed area) from total wall surface: 19%, approx. 120 m^2. Heating or cooling area (living area) is 257 m^2, but total area is 772 m^2. All the main materials and thermal parameters of reference building are given in Table 1.

Fig. 1. Reference building: typical three-storey residential building in Latvia (build in 1960s)

Table 1.

Main parameters and thermo-physic properties of building envelope

Construction of building	**Materiāls**	**Area, m^2**	**Heat-transfer coefficient U, W/m2K**	**Specific heat losses H, W/K**	**Density ρ, kg/m^3**
Front wall	brick + plaster	161	1,067	171,9	1400
Facade	brick + plaster	346	1,067	368,9	1400
Attic	planking + slag	230	0,681	156,7	800
Cellar	concrete + slag	198	0,91	128,9	1400
Old windows	wooden frame	67	2,381	144	-
New windowd	plastic frame	53	1,9	91	-
Street door	Wooden door	3	3,704	11,11	

The air exchange rate is 0.545 h^{-1}. Specific heat losses via enclosed constructions of building are 1072.2 W/K, but total specific heat losses of building included ventilation, doors, roof, walls and windows are 1509.8 W/K. There are 12 resident inhabitants. Internal gains from lighting, appliances and metabolism considered 5078 W. It is about 57.6 kWh/m^2 annually.

Hourly internal temperature and cooling load of building

A previous developed model for building hourly cooling load calculation in Latvia based on the European Standard EN 15255:2007 „Thermal performance of buildings – Sensible room cooling load calculation – General criteria and validation procedures" (has a status of Latvian Standard) [2] is used in the paper to define the hourly cooling loads and demand as well as internal temperature of building, see Fig. 2.

For weather data of reference year are used hourly values of air temperature and solar radiation (global, direct and diffuse) for the whole year.

This developed calculation model allow to appraise dynamic heat exchange processes and precisely find out heat amount to remove from building based on set internal temperature. Another output of this model is hourly internal temperature swing and changes including minimums and maximums.

For thermal mass characterization in the calculation model are used the equivalent thermal mass area (A_m, [m^2]), that includes the specific heat capacity C_m, (J/K) and internal heat capacity k, (kJ/m^2K) of each components of building envelope.

$$A_m = \frac{C_m^2}{\sum_{i=1}^{c} A_i k_i^2} \qquad (4)$$

where A_m is the equivalent thermal mass area, C_m is the heat capacity of the component for a 24 h period variation, A_i is the area of component *i*, k_i is the equivalent areal internal heat capacity of component *i*.

In the effective use of energy, the environmental temperature, solar radiation intensity purpose of use of spaces and characteristics, dimensions and formations of structure elements forming building shell are important parameters [7]. The thermal mass of the building elements influence considerably the temperature deviations that appear inside the building. As a result, a more unaffected indoor environment can be achieved.
Hourly cooling load is estimated when internal temperature of building is equal or higher 22 °C (set-point temperature). Actually this cooling load show amount of heat that is necessary to remove from building to provide good thermal comfort and microclimate for residents. Internal temperature exceeds 22 °C only 389 hours of the whole reference year (total 8760 hours). Total cooling demand is about 26 kWh/m^2 annum; this is about 72 GJ of heat that should be removed from building in whole year. Mostly surplus heat arises in summer season (see Fig. 2.). For comparison real heat demand for this building is around 190 kWh/m^2 annum (528 GJ).

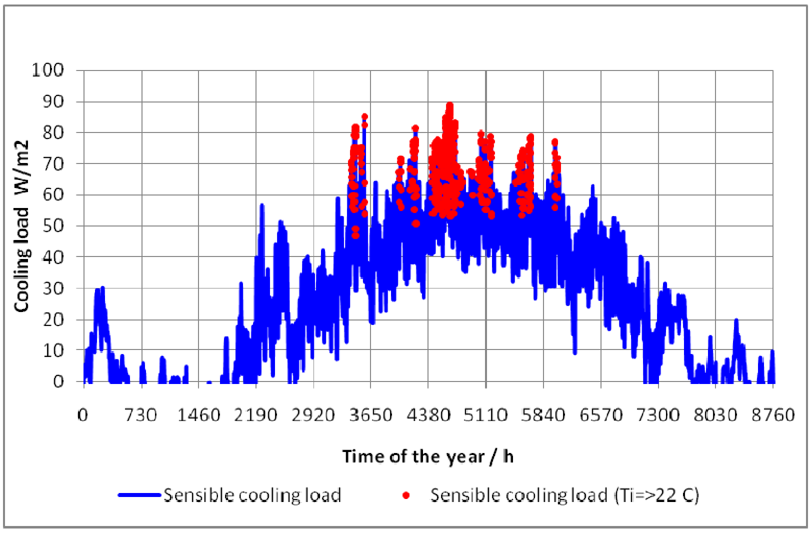

Fig. 2. Hourly cooling load of building in reference climatic conditions

From physical considerations it is well known that actual processes by which heat transfer takes place are conduction, convection and radiation [6]. The thermal reaction of building construction surface is mainly due to the mass behavior of building material and their structure.

Thermal inertia and thermal mass of building

Thermal inertia depend on thermal mass of building construction, but thermal mass is a function of material density (ρ, [kg/m^3]) and specific heat (c_p, [kJ/(kgK)]) and is a measure of the heat storage capacity of the material.
The characteristic thermal inertia factors and more specifically: (a) the decrement factor (f, [-]) – the decreasing amplitude of the thermal wave during its propagation process from outside to inside and (b) the time lag (φ, [h]) – the time it takes for a heat wave, with period P (24-h), to propagate from the outer surface (minimum or maximum external temperature peaks) to the inner surface (minimum or maximum internal temperature peaks) of the wall formation.
These parameters are very important, especially during the warm period of summer (when passive cooling is essential), when a periodic thermal wave propagates through a wall's cross sectional area, from its outer to its inner surface [1,3,4,5,6,7].
The heat storage capacity, decrement factor and the time lag of a building structure can be utilized for balancing the indoor temperature. In Fig. 3, there is simple propagation of a periodic heat wave from the exterior to the interior surface of a wall.

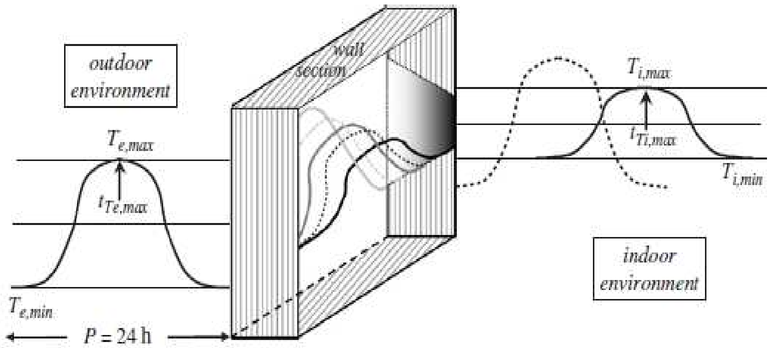

Fig. 3. Propagation of a periodic heat wave from the exterior to the interior surface of a wall [4]

Difference between external and internal temperature is described with decrement factor f and time lag φ – the thermal inertia factors of the building.

$$\varphi = t_{T_{i,\min}} - t_{T_{e,\min}} \quad (1)$$

$$\varphi = t_{T_{i,\max}} - t_{T_{e,\max}} \quad (2)$$

$$f = \frac{T_{i,\max} - T_{i,\min}}{T_{e,\max} - T_{e,\min}} \quad (3)$$

where $t_{T_{i,\min}}$, $t_{T_{i,\max}}$, $t_{T_{e,\min}}$ and $t_{T_{e,\max}}$ represent the times when external and internal temperatures are at their minimums and maximums, respectively. In addition, $T_{e,\min}$, $T_{i,\min}$, $T_{e,\max}$ and $T_{i,\max}$ are the minimum and maximum developed temperatures on both –internal and external side.

The variation and swing of the external environmental temperatures result to a heat propagation process by a periodic thermal wave (thermal excitation or thermal vibration or thermal load) from the outside to the inside of a wall with the flux always taking place from the hotter to the colder surface of the cross section arrangement of the wall. The thermal wave, which propagates from the external (entry) to the internal (exit) surface of the wall, is diminished and shows a time delay (phase difference) which is due to the thermal mass of the materials.

Time lag φ (or phase lag or time shift or time delay) is defined as the time required for a heat wave, with period P, to propagate through a wall from the outer to the inner surface, is actually the time required for the heat to pass through a material. On the other hand, decrement factor f (or decreasing ratio or dimensionless amplitude or temperature attenuation) is defined as the decreasing ratio of its temperature amplitude during the transient process of a wave penetrating through a solid element [4,6] and it is the measure of the damping effect: the higher the thermal capacity or the higher the thermal resistance of a material, the potent is the damping effect.

Thermal mass of building, including thermo-dynamic properties and thermal inertia of building envelope, affects the indoor temperatures in buildings [1].

Results and discussion

In this paper decrement factor f and time lag φ is investigated only for three days (72 hours, time of the year from 4585 to 4657 hour). July is one of the warmest mounth where ambient temperature can sometimes exceed 30° C.

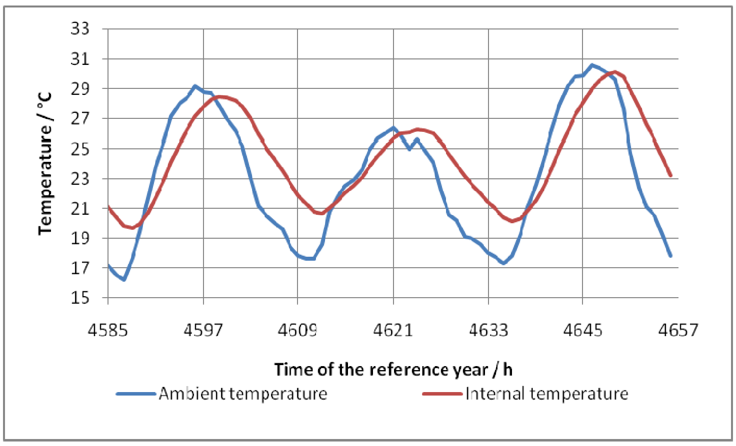

Fig. 4. Swing and offset of external and internal temperature in July before improve thermal mass of building

From Fig. 4, we can observe swing and offset of external and internal temperature and from Fig. 5 – hourly cooling load fluctuations in July in typical residential three-storey building in Latvia (that is – the real thermal mass of building before improving). Heat amount that is necessary remove from building in three days to provide set-point internal temperature (equal or less than 22 °C) is 13.3 MJ/m2 (10,33 GJ).

Simple energy efficiency measurements like insulation of walls mostly decrease only thermal transmittance (U, W/m^{2}K) or increase thermal resistance (R, m^{2}K/W) of building due to increase of thickness of the walls. There are several practical opportunities how to increase thermal mass of building without changing U or R values, e.g. Phase Change Materials and etc.

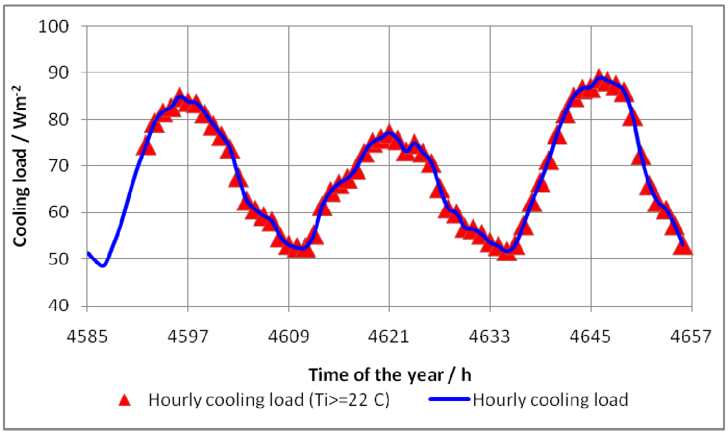

Fig. 5. Hourly cooling load fluctuations in July before improve thermal mass of building

In this paper we increase thermal mass by 20 % but thermal transmittance stay at the same level. It means we increase internal heat capacity of components to accumulate heat and give it back later. An also cause to the decreasing of the energy demands (proper forecast and utilization of cooling power and low energy cooling).

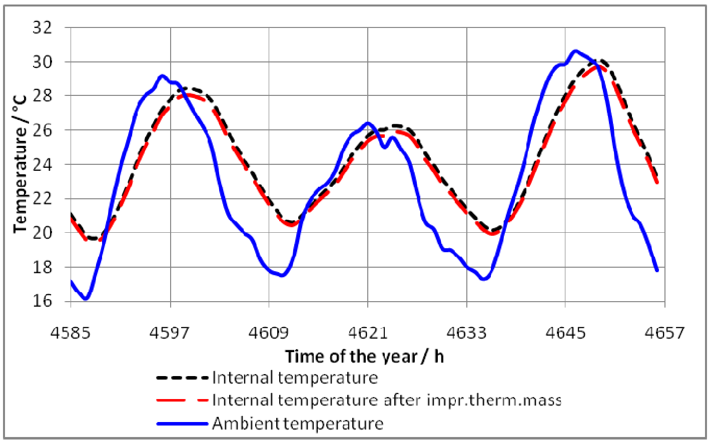

Fig. 6. Internal temperature swing before and after improving thermal mass

In table 2 are collected the decrement factor f and the time lag φ before and after imrpoving thermal mass of building. Results show that after improvement of thermal mass internal temparture fluctuation amplitude decrease (the decrement factor f decrease from 0.69 to 0.67), in other words, maximum temperature decrease, but minimum temperature increase (see Figure 6). Average difference between internal temperature before and after imrpoving thermal mass is more than 1 %.

Table 2.

The decrement factor f and the time lag φ for building

Parameters	The decrement factor f, non-dimensional quantity	The time lag φ, h	
		Min	Max
Before improving thermal mass of building	0.69	1.3	3
After imrpoving thermal mass of building	0.67	1.3	3

Study on cooling load showed that after improving of thermal mass, removable heat is around 13.25 MJ/m^2 (10.23 GJ) compare with actual 13.3 MJ/m2 (10,33 GJ).

Conclusions

Our analyses shows that quantity changes of decrement factor, time lag and cooling load due improving thermal mass is logical, but unfortunately non-essential. There could be several reasons, for example, too high thermal mass of reference building, too high or too low internal gain etc.

The influence of thermal mass – mediated time lag and decrement factor – on cooling load of building is studied using previously developed calculation model, which allows investigating the hourly cooling load and power of building and thermo-dynamic processes in construction of building.

Analyses evaluate the dependence of the cooling load on the thermal properties of thermal mass and external temperature, as well as the internal heat gain. Results show that typical residential building with rather low internal gains and small glazed area have also sensible cooling load. Clearly, for new buildings and especially for office buildings with large glazed area and high internal loads cooling load is essential energy management and comfort issue.

Increased specific heat and density (actually improved thermal inertia) of building construction unsubstantial reduce heat amount that is necessary remove from building to provide good conditions for residents. This unessential reduces cooling load peak and overall cooling energy demand and swing of internal temperature as well (decrease amplitude of fluctuations caused by ambient temperature, see Figure 6).

Improve of thermal mass decrease decrement factor f. It means decreasing of internal temperature fluctuation amplitude. There is no influence on time lag (Table 1). It may be concern with used time step (one hour) in calculation.

Improve of thermal mass causes little decrease (in average by 1.2 %) of cooling load compare with real cooling load. The defined improvement of thermal mass has not significant influence (difference is approximately 1-1.5 %) on cooling load and internal temperature (see Figure 6) of the building.

Findings and acquired results show that thermal inertia has not significant influence on cooling load (cooling load decrease if improve thermal mass) and internal temperature fluctuations (the decrement factor decrease if improve thermal mass) in this situation (old residential building with relative small internal gains).

In Latvian climatic conditions it is necessary find optimum thermal mass of building envelope because there still is plenty high heat demand.

Right selection of insulation and materials can not only decrease heat losses and respond to temperature variations and heat fluxes from outside to inside and vice versa. Thermal inertia and thermal mass is rather attractive for new buildings, but in some cases it can be used in renovation of existing buildings.

There is necessary to continue and expand started investigation and research to identify all parameters and conditions when thermal mass influence on cooling load would be significant, for example, office buildings or public buildings with large glazed area or high internal gains.

References

1. L. Yang, Y. Li. Cooling load reduction by using thermal mass and night ventilation // Energy and Buildings – ELSEVIER, 2008 – [40] P. 2052-2058.
2. D. Jaunzems, I. Veidenbergs. Development and Verification of Method for Building Cooling Load Calculation for Latvian Climate Conditions // 49th International Scientific Conference of Riga Technical University, October 11 – 13, 2008, Riga, Latvia.
3. K.J. Kontoleon, D.K. Bikas. Thermal mass vs. thermal response factors: determining optimal geometrical properties and envelope assemblies of building materials // International Conference "Passive and Low Energy Cooling for the Built Environment". May 2005. – Santorini, Greece. – P.345-350.
4. K.J. Kontoleon, E.A. Eumorfopoulou. The influence of wall orientation and exterior surface solar absorptivity on time lag and decrement factor in the Greek region // Renewable Energy. – ELSEVIER, 2008. – [33] P.1652-1664.
5. M.M. Vijayalaksmi, E. Natarajan, V. Shanmugasundaram. Thermal Behavior of Building Wall Elements // Journal of Applied Sciences, 2006 – 6 [15] P.3128-3133.
6. K.J. Kontoleon, D.K. Bikas. The effect of south wall`s outdoor absorption coefficient on time lag, decrement factor and temperature variations // Energy and Buildings – ELSEVIER, 2007 – 39 [2007] P.1011-1018.

7. K. Ulgen. Experimental and theoretical investigation of effects of wall`s thermophysical properties on time lag and decrement factor // Energy and Buildings – ELSEVIER, 2002 – 34 [2007] P.273-278.

Удельное потребление теплоэнергии в жилых зданиях равно 200-225 кВт·ч/м^2 в год, потребление электроэнергии одной хозяйстве 1000-1200 кВт·ч в год. С повышением требований к уровню комфорта и увеличением количества площадей с застеклёнными поверхностями, а также с повышением интереса к обеспечению должного микроклимата в зданиях, всё чаще уделяется внимание охлаждению зданий и связанными с этим процессами теплообмена. Термическая инерция и термическая масса ограждающих конструкций зданий являются одними из главных факторов, влияющих на амплитуду и период колебаний температур в помещениях в зависимости от внешней температуры.

Dzintars Jaunzems, Ivars Veidenbergs, Ēkas ārējo norobežojošo konstrukciju siltumtehnisko īpašību un termiskās inerces ietekme uz ēkas aukstuma slodzi

Ēkas veido apmēram 30 % no visa Latvijas gala enerģijas patēriņa. Īpatnējais siltumenerģijas patēriņš ir 200-225 kWh/m^2 gadā, savukārt vidējais vienas mājsaimniecības elektroenerģijas patēriņš ir apmēram 1000-1200 kWh/gadā. Pieaugot prasībām pēc komforta un palielinoties ēku stikloto virsmu laukumam, kā arī pastiprinātai interesei par mikorklimata nodrošināšanu ēkās, arvien vairāk tiek pievērsta uzmanība ēkas aukstuma slodzei un ar to saistītiem siltumapmaiņas procesiem. Ēkas norobežojošo konstrukciju termiskā inerce un termiskā masa ir vieni no galvenajiem faktoriem, kas būtiski ietekmē iekštelpas temperatūras svārstību amplidtūtu un periodu atkarībā no ārgaisa temperatūras.

Dzintars Jaunzems, Ivars Veidenbergs, Influence of thermo-dynamic properties and thermal inertia of the building envelope on building cooling load

Buildings are responsible for about 30 % of the total energy consumption of Latvia. Specific heat consumption is 200-225 kWh/m2 per annum, for its part the average consumption of one household is about 1000-1200 kWh per annum. Due to increasing needs for comfort, an increase in the total area of buildings covered by glass, as well as intensified interest in establishing a good microclimate in buildings, there is also increasingly more attention paid on to the cooling load of buildings and the related heat transfer and exchange processes. Thermal inertia and the thermal mass of building envelope are main factors, which substantially influence the amplitude of changes in temperature and the period during which the internal temperature is dependant on the external temperature.

Дзинтарс Яунземс, Иварс Вейденбергс, Влияние теплотехнических свойств и термической инерции граждающих конструкций зданий на охлаждающую нагрузку здания

Потребление энергии в зданиях составляет около 30% от суммарного потребления энергоресурсов в Латвии.