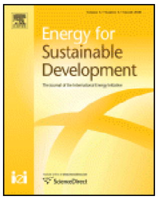
Energy for Sustainable Development 29 (2015) 38–46

Contents lists available at ScienceDirect

Energy for Sustainable Development



Redeveloping industrial buildings for residential use: Energy and thermal comfort aspects

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ARTICLE INFO

Article history:
Received 14 July 2014
Revised 18 May 2015
Accepted 12 September 2015
Available online xxxx

Keywords:
Building redevelopment
Energy demand
CFD
Glazing
Thermal comfort

ABSTRACT

The old industrial buildings, now located near the city centres, redeveloping into commercial or residential use is very popular, but energy and especially comfort conditions not analysed because usually the specific projects are not made. This article provides an analysis of various aspects of energy demand and indoor thermal comfort when old, often unused industrial buildings are redeveloped for residential use. The results of the analysis, if the buildings are in use, show such redevelopment to be very efficient in terms of saving energy resources. In order to analyse thermal comfort of the redeveloped building, two different heating systems, radiator heating and floor heating, were examined. The performance of these systems was analysed with respect to three different room heights and window-to-wall ratios (hereinafter referred to as WWR). In order to simulate temperature distribution, computational fluid dynamics (hereinafter referred to as CFD) software SolidWorks®FlowSimulation was used. The results of the research demonstrate the acceptability of the heating systems in terms of indoor climate and thermal comfort as well as facilitate further discussion for future research in the field.

Introduction

A great deal of old unused industrial facilities built in the Soviet era exists in various towns of Lithuania and in other Eastern European countries alike. These buildings are usually large in volume (i.e., tall and big facilities) and large areas of the façades of these buildings are glazed (Fig. 1). In Lithuania a lot of these buildings were constructed in the downtown area; beneficial location and features of the industrial architecture resulted in the fact that instead of demolishing these buildings they are now being redeveloped in order to convert their building type to administrative or residential, the latter being the most common. In order to keep the industrial style intact, the window area is not amended during the redevelopment (Fig. 2).

Redevelopment of old industrial buildings used for production or storage to new residential homes increases energy efficiency of said buildings and helps to solve the issue of sustainable urban development while maintaining the specific industrial style of the buildings.

Such projects have already been launched, but due to lack of experience, the specifics of apartment buildings with high ceilings and large glazed areas are not always taken into account when designing heating systems that should ensure sufficient thermal comfort.

Large glazing areas are typical of newly constructed buildings as well. The transparency of the façade not only provides a unique architectural effect but also creates a pleasant visual contact with outdoors, natural lighting and potential energy savings in terms of lighting, provided that the systems function properly (Ge and Fazio, 2004). However, the still relevant tendency to use a fair amount of glass in the façade results in certain problems as well (Goia et al., 2013). First of all, such buildings are not energy efficient: in summer, they require more energy for cooling, whereas in winter, more for heating. Another problem that has been proved by a great deal of research is the difficulty of ensuring proper indoor thermal comfort near large glass partitions (Ge and Fazio, 2004; Kim et al., 2007; Šeduikytė and Paukštys, 2010; Jurelionis and Isevičius, 2010; Hassan, 2012). Due to these reasons, window size should be optimised following certain criteria (Ochoa et al., 2012; Menzies and Wherrett, 2005). A lot of research has been conducted in order to examine the effects of the area and characteristics of glazing on heat transfer through partitions as well as energy savings (Susorova et al., 2013; Poirazis et al., 2008; Jaber and Ajib, 2011; Jonsson and Roos, 2010). To summarise the aforementioned research, it can be concluded that large glazed façades are undesirable except in cases of double façades or smart glazing such as PCM (Goia et al., 2013; Coussirat et al., 2008).

One the main difference between newly constructed buildings and old redeveloped factory buildings is that great height (volume) is typical to the latter. It is well-known that buoyancy-driven currents cause heterogeneous air temperature and velocity fields in large-volume rooms (Šeduikytė and Paukštys, 2010). Due to convection, warm air tends to move upwards thus creating a positive temperature gradient between the floor and the ceiling. This phenomenon is known as stratification and is especially typical to the high and large-volume buildings (e.g., airship hangars, high schools, atriums, lofts, factories, etc.) (Said et al., 1996). A few authors who analysed different types of large-volume buildings (i.e., factories, airship hangars, aviaries) that measure from

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http://dx.doi.org/10.1016/j.esd.2015.09.004

Fig. 1. Example of old unused industrial buildings in Vilnius.

Fig. 2. Examples of industrial buildings in Vilnius redeveloped into residential buildings.

6 m to 17 m in height discovered that the temperature discrepancy between the floor and the ceiling amounts from 5.6 °C up to 20 °C, whereas in the buildings that have atriums, this discrepancy amounted for only up to 2 °C (Said et al., 1996). The problems of cold air development and stratification are especially relevant in cases of residential large-volume rooms with large windows.

Both the stratification phenomenon and thermal comfort depend on the heating system installed in the building. The most common heating systems for residential and administrative buildings in the European Union are water based (Ploskić and Holmberg, 2011). Traditional radiator heating systems are also planned and designed for the buildings that are being redeveloped into residential buildings, a fact that suggests that thermal comfort in such buildings is poor. It would seem that tall and large-volume rooms should benefit most from floor heating since this way the vertical temperature gradient is negative (Karadağ et al., 2007). In comparison with other heating systems, floor heating systems have been used for a very long time because of such benefits. A study in Sweden has also demonstrated that low-temperature enhances thermal comfort since it leads to lower air agility and lower temperature difference as compared to high-temperature radiator heating (Myhren and Holmberg, 2008). Cold air currents that form near glass partitions and cause discomfort may be blocked by providing warm air nearby (Zukowski, 2007). Ge and Fazio (2004) presented an experimental study on comfort in a carcass building with a large one-piece glazing area in the façade and drew conclusions that in order to avoid formation of cold air currents near windows one should install perimeter heating near the base of glazing.

Due to the reasons mentioned above, the choice of the heating and ventilation systems for large-volume and tall buildings is of crucial importance. A detailed assessment of thermal comfort in such buildings is performed using the CFD analysis that requires expert mathematics and computer knowledge. Consequently, methods that are simplified and suitable for practical application in engineering should be discovered and applied. For example, Voeltzel et al. (2001) developed AIRGLAZE, a research code that is intended to analyse thermal processes of large highly-glazed spaces, the object of this article.

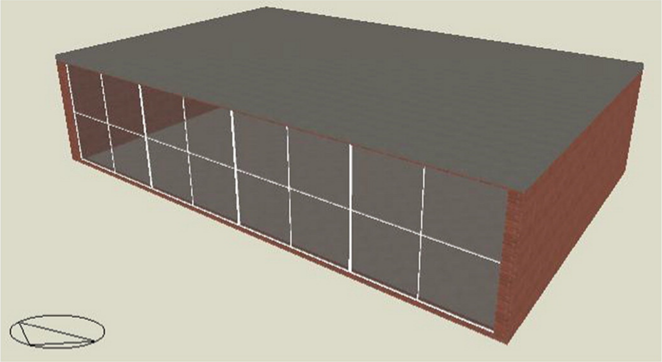


Fig. 3. Model of the room used for simulation.

Table 1
Simulation input data.

Case	Room height, m	U-values	Ventilation system	Total air change rate	Orientation
Redeveloped: new residential	2.8	$U_{window} = 1.68$ W/m^2 K $U_{wall} = 0.22$ W/m^2 K Roof, floor, eastern and southern walls are assumed to be adiabatic	Natural	$n = 0.2$ 1/h	North
Existing, non-redeveloped: industrial		$U_{window} = 2.48$ W/m^{2}K $U_{wall} = 1.00$ W/m^{2}K Roof, floor, eastern and southern walls are assumed to be adiabatic	Mechanical + infiltration, without heat recovery	$n = 1.0$ 1/h	

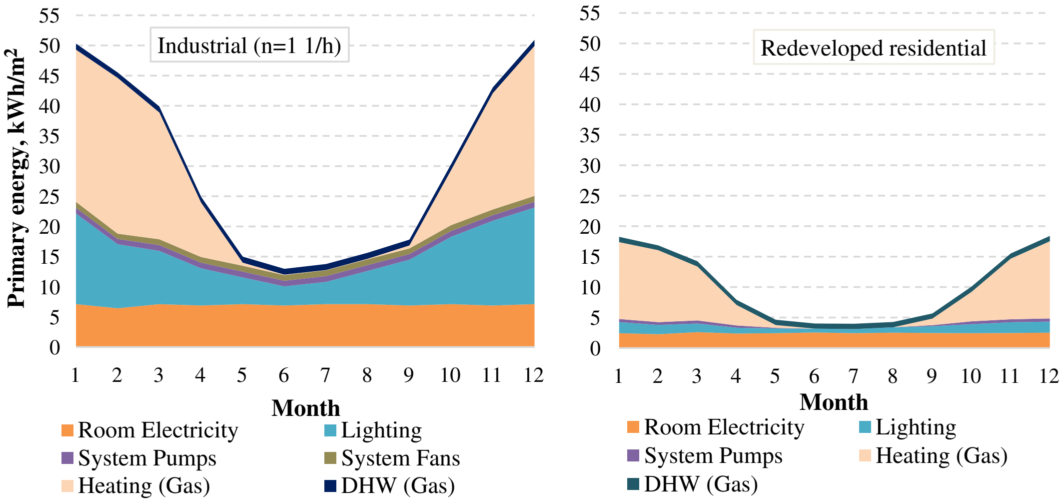


Fig. 4. Annual primary energy demand.

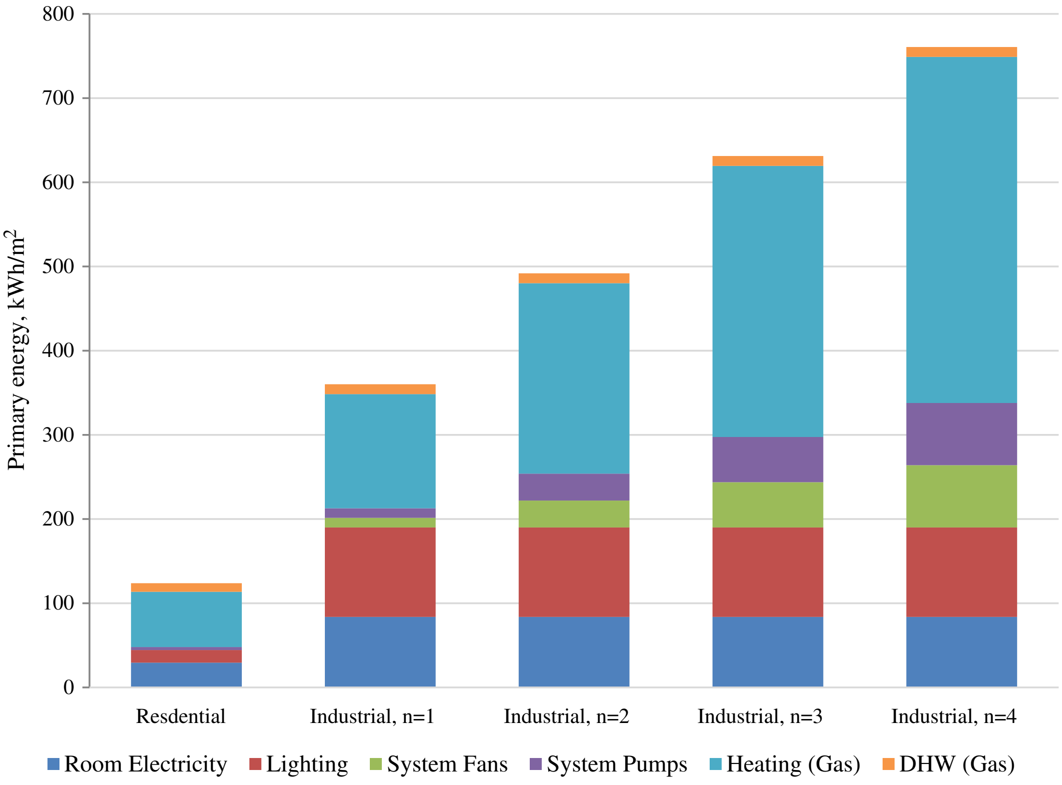


Fig. 5. Annual primary energy demand for different cases and air change.

Table 2
Basic and alternative models data.

	Model	Type of heating	Room height (m)	Glazing	Heating power (W)
Figs. 6 and 7	Basic	Radiators	2.8	Windows (26 m^2)	~2300
Figs. 8 and 9	Alternative	Radiators	2.8	Fully glazed	~4000
Figs. 10 and 11		Floor heating	2.8		~4000
Figs. 12 and 13		Radiators	4.6		~7000
Figs. 14 and 15		Radiators	7.1		~11000

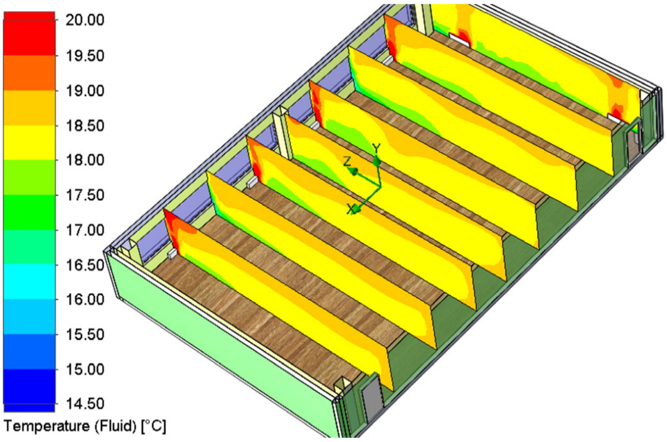


Fig. 6. Vertical temperature distribution in a room of 2.8 m height with a partially glazed partition wall.

Object and boundary conditions

The target room (a part of a building) of this study is a part of a currently redeveloped museum (the building was classified as industrial since 1901 and as a museum since 2003), the aggregate room area of which is 246.5 m^2 (19.8 m × 12.45 m). The room has two external walls, one is opaque and the other has a glazed surface (Fig. 1). The heat transfer coefficient is $U = 0.22$ W/m^2 K for the opaque external partition and $U = 1.68$ W/m^2 K for the transparent external partition (i.e., a window).

The building where the aforementioned room is located is based in Vilnius (Lithuania); therefore, the external temperature to be calculated is −23 °C, according to the Lithuanian climate normative. The floor, ceiling and two internal walls of the room adjoin the adjacent rooms with the temperature of +19 °C.

The heating system load of the room equals heat losses of the room under the aforementioned boundary conditions.

Energy demand aspects

The actual operational data of the existing old soviet era buildings usually are unknown because of the lack of measuring equipment and energy management, so energy demands can be estimated by asset rating and /or simulation.

Fig. 3 presents the shape and a model of the building simulated with DesignBuilder®. The building in the simulated case is residential (and, according to national regulations STR 2.05.01:2013 (2013), it corresponds with energy class B) and is compared to the simulated energy demand of a non-redeveloped industrial building at the average room temperature (after evaluating the reduction of temperature), i.e., 19 °C. The main input data, influencing the thermal balance of the simulated variants, is provided in Table 1.

The ventilation air change rate has the greatest influence on energy demand. In newly constructed and renewed residential buildings, the air

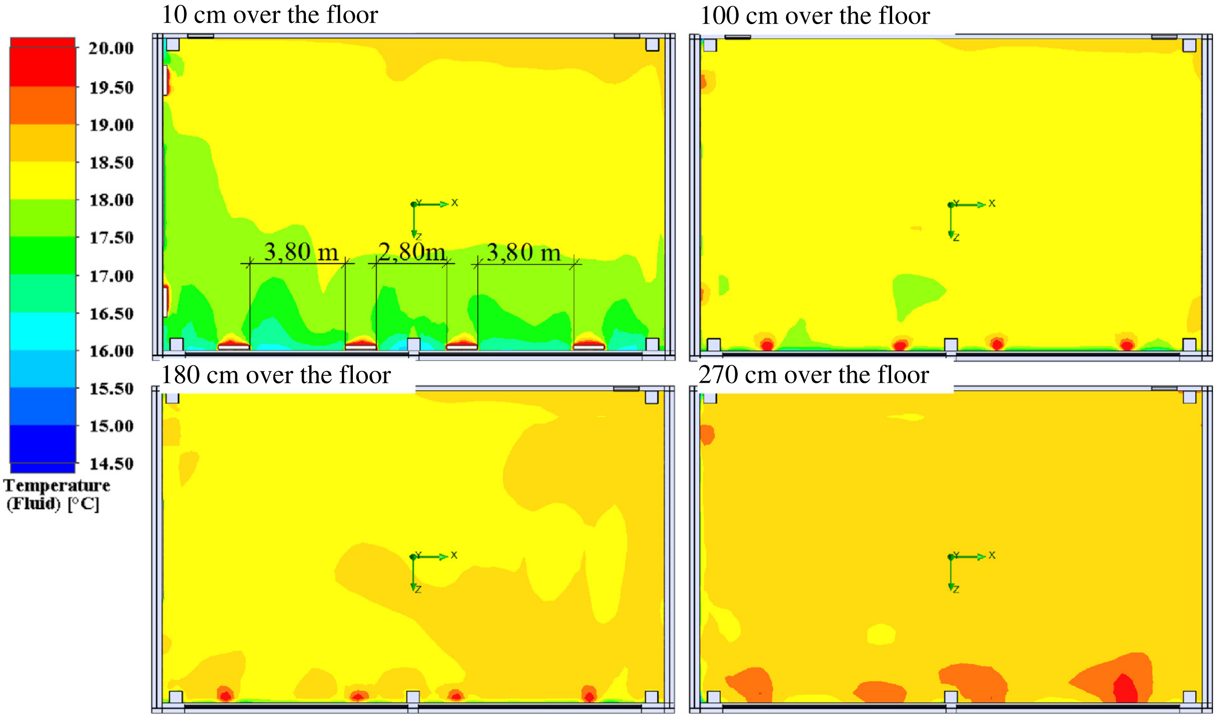


Fig. 7. Horizontal temperature distribution in a room of 2.8 m height with a partially glazed partition wall.

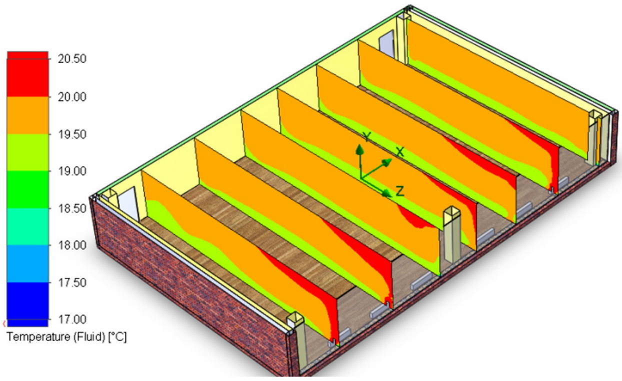


Fig. 8. Vertical temperature distribution in a room of 2.8 m height with a fully glazed partition wall (heating devices—radiators).

change rate is determined not only by mechanic ventilation but also by their relatively high air tightness. Meanwhile, mechanic ventilation is necessary to industrial buildings due to harmful or explosive substances being released during processes that take place there. Depending on the specifics of said processes, the ventilation air change rate of industrial buildings may amount to 1 to 30 l/h (Hall and Greeno (2011).

Since production buildings are used for various purposes, including storage, assembly of furniture, garaging, etc., and rarely involve active production, it is considered that air change rate in them is relatively low, compared to potential rate in industrial buildings.

Fig. 4 shows the structure of primary energy demands of the existing building (when the electricity factors of primary energy are considered to be 2.8, and thermal factors are considered to be 1.1), when the air change rate is 1. For comparative purposes, energy demands of the same building when it is renewed and redeveloped to a residential building are also presented. Residential buildings do not have energy demands for ventilation system fans since these buildings are not absolutely airtight and are ventilated naturally. The most significant discrepancies are observed when comparing the energy demands for lighting and heating of the industrial building redeveloped to residential. Such significant difference between these constituents of the energy balance results from an efficient LED lighting system designed for the renewed building as well as from the significantly higher heat transfer coefficient and a lower air change rate.

Since air change rate is one of the most important factors that influence thermal demands of a building and various non-intensive process may take place in old industrial buildings, air change rate in these buildings can realistically be considered to be the same as that of an open plan spacious factory, i.e., from 1 to 4 l/h (Hall and Greeno, 2011). Thus, additional energy demands are also simulated under varying air change rates: from $n = 1$ to 4 l/h.

Results provided in Fig. 5 show that redeveloping industrial building to residential, renewing its partitions, and increasing air tightness, from 5 to 20 (!) times, respectively, leads to a 3 to 5 times lower primary energy demand (depending on the air change rate) when compared with the existing, non-redeveloped industrial building.

Aspects of thermal comfort

In the presented study, the commercial finite volume tool 'SolidWorks® FlowSimulation' was used to perform the simulations, whose goal was to examine the performance of two different heating systems at large-volume rooms with different height and WWR values. Table 2 presents the basic and the alternative models data for thermal comfort analysis made.

Base case model

In the model of this variant (Fig. 6), the height of the room measures 2.8 m; over the entire *Z* axis, there stretches the window zone (partially glazed partition) that measures 1.5 m in height and 26 m^2 in area. In terms of heating devices, there are 6 radiators with the aggregate heat load of 2300 W.

The average temperature of the simulated room is +18.3 °C. The vertical distribution of temperatures is demonstrated in Fig. 6, the horizontal distribution in Fig. 7.

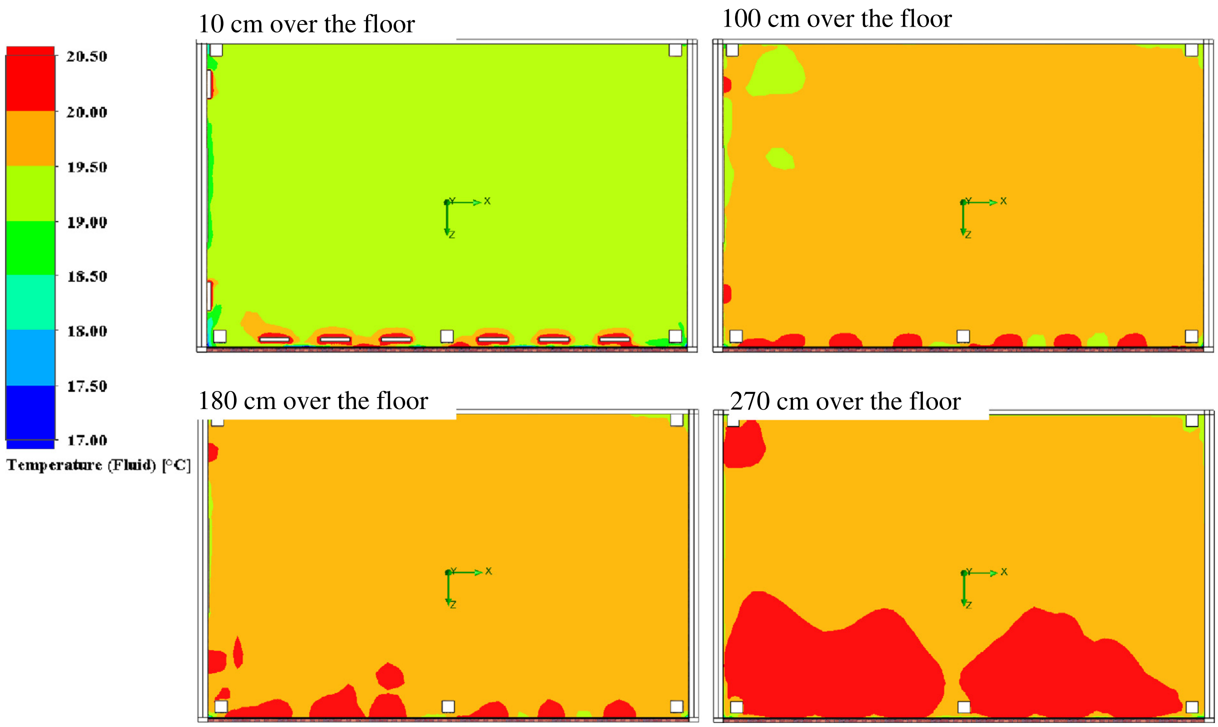

10 cm over the floor
100 cm over the floor
180 cm over the floor
270 cm over the floor

Fig. 9. Horizontal temperature distribution in a room of 2.8 m height with a fully glazed partition wall (heating devices—radiators).

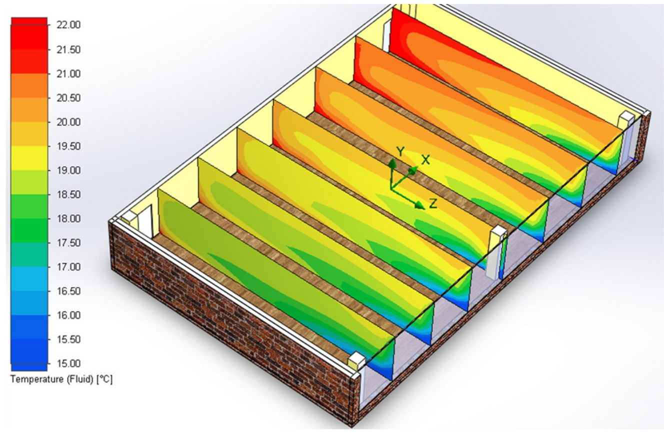


Fig. 10. Vertical temperature distribution in a room of 2.8 m height with a fully glazed partition wall (floor heating).

Temperature fields in various sections of the model show that the temperature distribution in the room fluctuates only slightly due to cold air that flows from the glass partition at 1.5 m height mixing with warm air. It can be said that comfort conditions are met, i.e., the difference between the surface temperature of the partition and the temperature in the range of 1 m does not exceed 2 °C. A more significant difference can be observed in the section that is 270 cm in width, where sparsely located more powerful devices exude greater currents of hot air that do not have time to mix with the air in the room; thus, zones of slightly higher temperature emerge near the ceiling.

Compared alternative models

The primary analysis involved 14 different variants of models in total; various variables were modified, such as the area of the glazing, the height and type of windowsills, the location of heating devices, etc. This article presents and analyses the most distinctive and scientifically interesting versions of the models.

1. Figs. 8 and 9 show the results of temperature fields in a variant that is analogous to the basic variant (where the room measures 2.8 m in height) except that windows are replaced with shop-windows (the glazing area is 55 m^2) and the load of heating devices is increased to 4000 W due to a larger glazing area and heat losses. All heating devices are located near the glass partition.

The analysis of the temperature fields shows that the air temperature in the room fluctuates for about only 1.5 °C, which is an unexpected result. The temperature distribution in this experiment is similar to that of the previous variant of the model, and it is observed that the installation of a shop-window that measures 2.8 m in height does not have any negative influence on the indoor climate (no cold air currents exuded by it can be observed). It is also noticeable that no colder currents pervade even at 10 cm height due to powerful heating devices constituting a kind of a warm air barrier. Naturally, such room requires more power in order to compensate for the heat losses incurred by the glazing but this does not influence the microclimate parameters negatively, and thus, colder air currents do not pass from the shop-window into the room.

2. Figs. 10 and 11 present the results of a variant of the model that is absolutely identical to Figs. 5 and 9; only the method of heating is changed from radiators to floor heating. A heat load of 4000 W that is required in order to increase the temperature of the room up to the standard +18 °C– +20 °C is distributed evenly in the whole area.

The analysis of the temperature distribution shows that the left part of the room is colder than the right. This can be explained by the fact that the left side is bound by the outdoor partition wall. A greater near ground penetration of cold air into the room is a big drawback of the floor heating, in comparison to models where radiators were installed. This is clearly demonstrated in the section at 10 cm above the floor (Fig. 11). The results show that the temperature distribution caused by floor heating near the glass partition (a shop-window) is not characteristic of that usually provided by manufacturers. The floor temperature should be higher but the cold air mass that flows from the glass partition moves the warmer air away. The cold air current (15 °C–17 °C) that flows near the ground penetrates the room by 3 to 3.5 m, which can cause discomfort in the occupied zone. However, the fact that this floor heating model is simplified and it is considered that the whole are of the floor heats up should also be taken into account since in real life a warmer floor heating outline is often installed

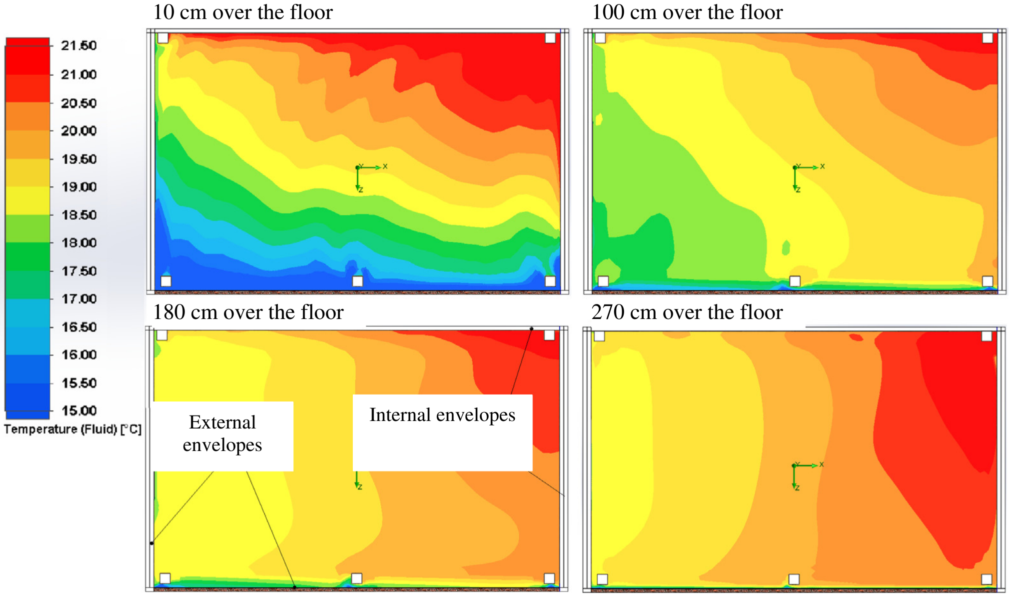


Fig. 11. Horizontal temperature distribution in a room of 2.8 m height with a fully glazed partition wall (floor heating).

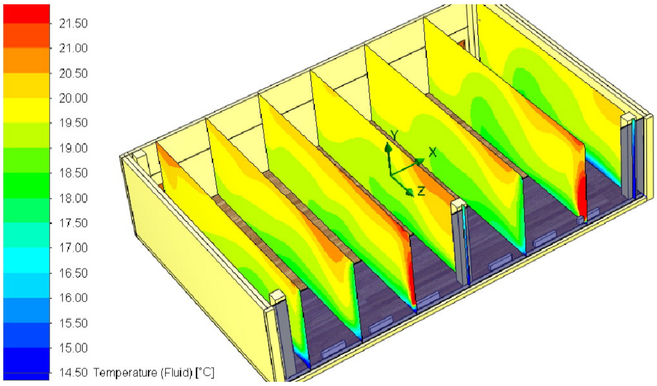


Fig. 12. Vertical temperature distribution in a room of 4.6 m height with a fully glazed partition wall (radiators).

near windows. Yet floor heat load for 1 m^2 does not usually exceed 100 W–120 W so it can be presumed that such floor heating would not preclude cold air convection currents and is, therefore, not suitable for the heating of such rooms.

3. This model (Figs. 12 and 13) is analogous to the No. 1, except that the height of the room and the glazing area are increased to 4.6 m and 91 m^2, respectively; the heat load is increased to 7000 W.

The colder air zone exuded by the glass partition near the ground is quite clear in this model, unlike in the model where the room measured 2.8 in height. The 14.5 °C–16 °C zone at 10 cm height from the glass partition has penetrated the room by 0.5 m. The radiators are located quite densely (the distance between radiators is 1.61 m, Fig. 13); the cold air current that is exuded by them acts as a warm air barrier that does not allow cold air to penetrate the room deeper. Thus, it can be presumed that in terms of comfort, the most acceptable solution is to install the heating devices in a continuous line along the whole partition wall. This model demonstrates another interesting phenomenon: the warmest zone is located not only near the ceiling but also near the unheated partition wall that is located in front of the shop-window, whereas the temperature inside the room is lower (Fig. 12). It can be explained by the fact that the higher the room, the more distinct the influence of gravitational forces is. In this case, the air heated by radiators rises up and, after coming into contact with the ceiling, it 'bends' and flows along the ceiling and, after coming into contact with the wall, it is 'forced' to fall down (the descent of air is influenced not only by dynamic forces, i.e., the velocity of the current, but also by the fact that it is cooling down, i.e., gravitational forces). It is also visible that near the ceiling of the model, in the height of 4.5 m, the temperature is higher by 2 °C than near the floor (at 10 cm height).

In conclusion, it would seem that radiator heating is suitable for heating rooms where shop-windows as high as 4.6 m are installed.

4. This model (Figs. 14 and 15) is analogous to No. 1 and No. 3, except that the height of the room is increased to 7.1 M; the glazing area is increased to 141 m^2, and the heat load increases to 11.000 W.

The analysis of the temperature distribution in the model shows that even though radiators are capable of maintaining the desired temperature, the warm air convection current that is exuded by them cannot 'resist' the cold air masses that pervade near the glass partition. Fig. 14 clearly shows how the colder air mass seems to move the warm air convection current exuded by radiators away (horizontally, in the direction of the interior of the room). If we compared this model to No. 3 (Fig. 12, room height measures 4.6 m in height), we would see the exact opposite: here the warm air convection currents that rise from the heating devices act as a warm air barrier that prevents colder air currents near the shop-window from pervading the room. Meanwhile, despite the fact that at first glance the temperature seems to be more evenly distributed and in the range of 0.5 m from the glass

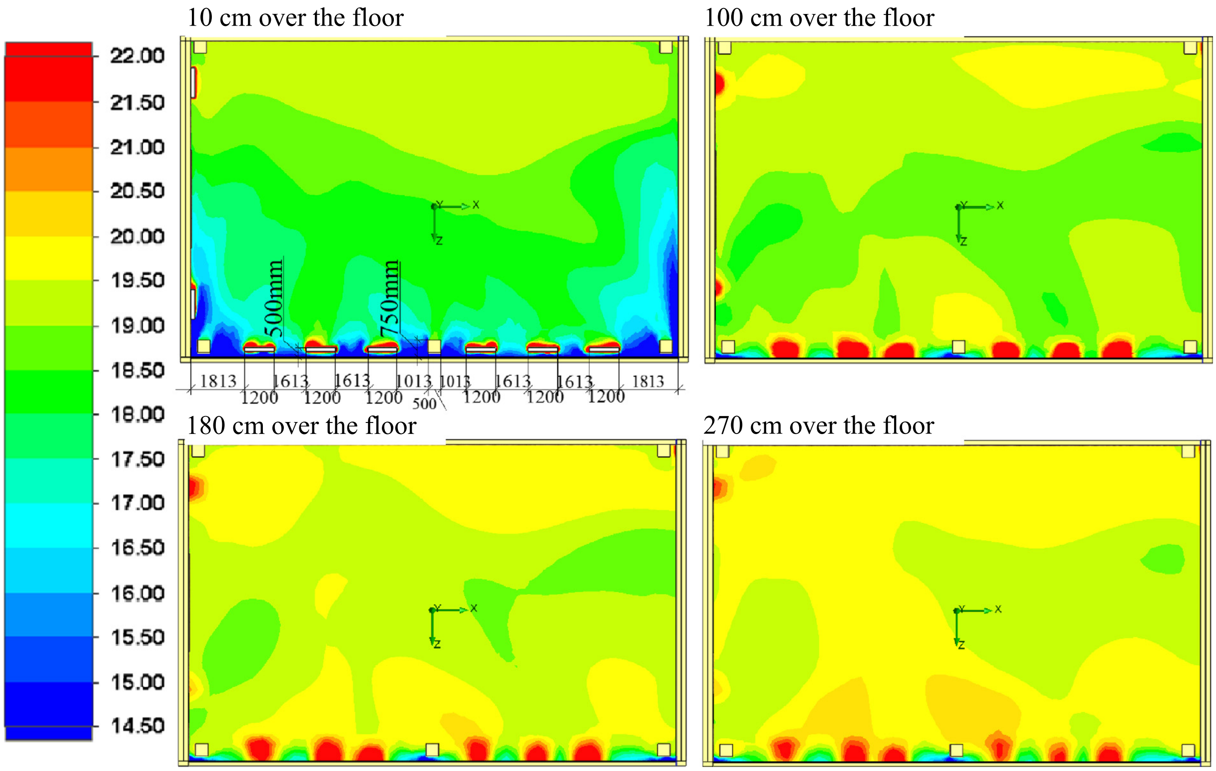


Fig. 13. Horizontal temperature distribution in a room of 4.6 m height with a fully glazed partition wall (radiators).

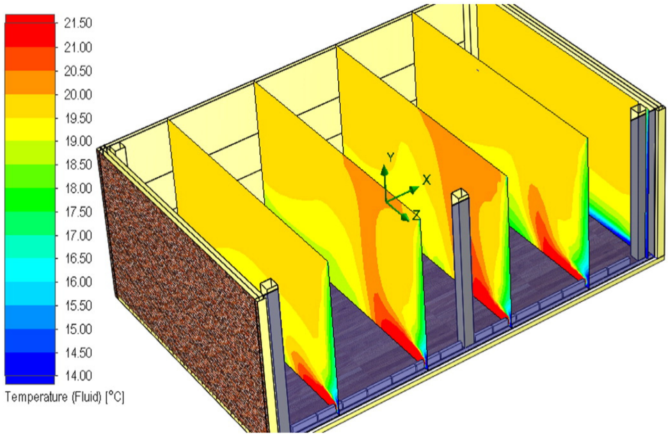


Fig. 14. Vertical temperature distribution in a room of 7.1 m height with a fully glazed partition wall (radiators).

partition the temperature increases from 16 °C to 18 °C in this model, it can be attested that radiator heating is not capable anymore to ensure the parameters of microclimate and to constitute a warm air 'barrier' that would prevent cold air currents near the shop-window from pervading the room. Thus, it can be concluded that radiator heating is not capable to ensure the thermal parameters of microclimate in a room that measures 7.1 m in height and has a shop-window/façade that measures 7.1 in height.

General conclusions and discussion

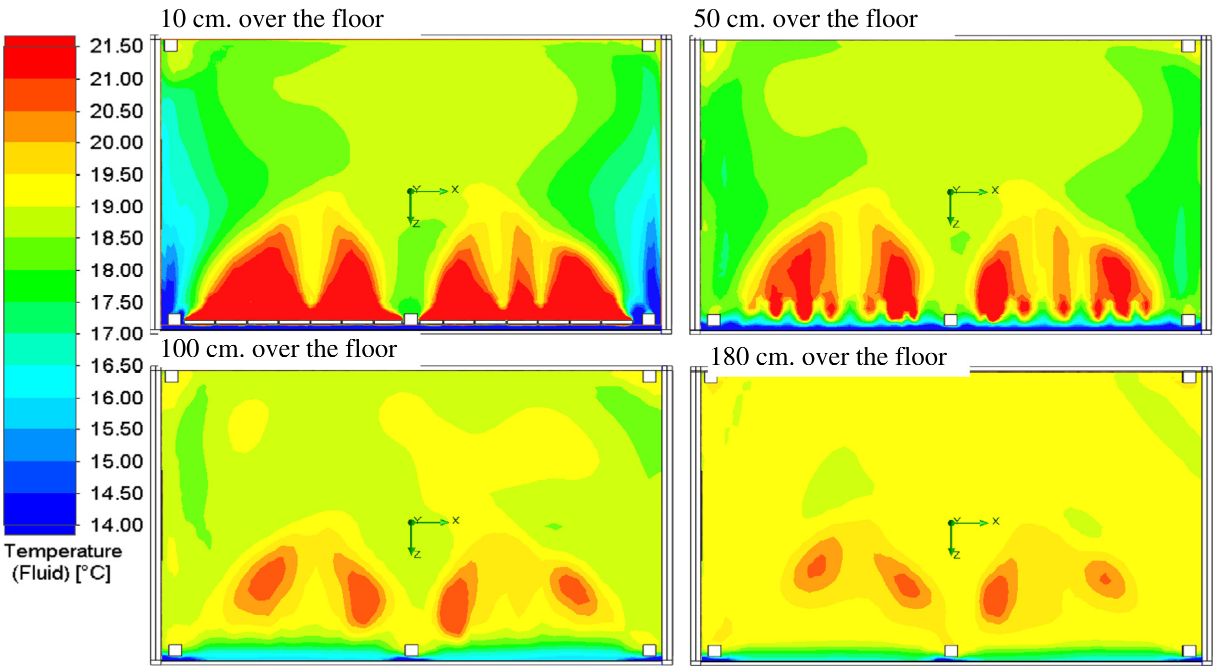
The results of the thermal comfort model allow drawing the following conclusions:

- In terms of thermal comfort floor, heating is an unsuitable method of heating for rooms with fully glazed (or partially glazed up to the floor) external partition walls since cold air current deeply penetrates the room and the whole zone near the glazed area becomes uncomfortable. It is recommended to design radiator (convection) heating devices additionally near glass partition walls in rooms where floor heating is to be installed.
- It is recommended to design radiator heating systems for rooms no higher than 4 m since due to the increased room height the warm convection current cannot 'resist' the cold air masses that descend near the glass partition. Installation of heating devices in a continuous line along the whole partition thus creating a 'warm air curtain' is also recommended since the gaps between the heating devices allow the cold air currents to deeply penetrate the room especially in the lower area of the room. Also, the danger of water vapour condensation arises as well.

One of the questions that require further research activity is the influence of ventilation system on the indoor climate of a room. Depending whether the system is mechanic or natural, the parameters of thermal comfort of the room such as temperature stratification, the velocity of air movement, etc., also change.

Another problem that should be discussed in the future is rather widespread in newly designed and redeveloped buildings. Heating devices in such buildings are often installed near a transparent partition (the radiator is visible from the outside). Thus, a significant portion of the heat (that may amount to 25%) is radiated directly to the outside and may not be used for maintenance of thermal comfort of the room; in a situation when the heat load is sufficient, the heat use of the room increases correspondingly.

With regards to energy, it can be said that with the redevelopment of a building to a higher energy class (so that it would comply with the requirements set for a passive building, i.e., 120 kWh/m^2 of primary energy, for example), the difference between the existing, non-redeveloped building and the building redeveloped to residential would equal 5 to 13 times. Thus, in order to use the well-developed infrastructure near old, non-renewed industrial buildings rationally and to reduce energy use while maintaining the specific style of industrial buildings, it is advisable to renew these buildings and to redevelop them into residential buildings.


10 cm. over the floor

50 cm. over the floor

100 cm. over the floor

180 cm. over the floor

Fig. 15. Horizontal temperature distribution in a room of 7.1 m height with a fully glazed partition wall (radiators).

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