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Building Performance Simulation of Industrial Hall with Excessive Heat Loads

Dynamická simulace vnitřního prostředí v průmyslové hale s nadměrnou tepelnou zátěží

Reviewer
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Numerical simulations are becoming an integral part of the design procedure of buildings, building systems and technologies allowing for not only evaluating the building energy demands and indoor quality but also for studying the influence of various design parameters and aspects of a building's internal microclimate. In this case study, a numerical simulation of an internal microclimate in an industrial building in the simulation software BSim 2002 was performed in order to assess the internal microclimate, examine the effect of precooling and determine the required cooling capacity. Furthermore, this article deals with the analysis of the influence of excessive internal gains caused by bogie-hearth chamber furnaces and their implementation into the simulation software. The results illustrate the minor effect of precooling for this case study and the insufficiency of the cooling capacity in the investigated industrial object.

***Keywords:** transient simulation; BSim; Industrial building; Internal microclimate; Chamber furnaces*

Dynamické numerické simulace se postupně stávají nedílnou součástí procesu návrhu budov a jejich technických zařízení. Tyto simulace nejen umožňují vyhodnocení energetické náročnosti návrhu budovy, ale také studium rozličných návrhových parametrů a aspektů vnitřního prostředí. V této případové studii průmyslového objektu sloužícího k tiskařským účelům bylo provedeno zhodnocení vnitřního prostředí, zjištění možného pozitivního vlivu předchlazování budovy upravovaným vnějším vzduchem a určení potřebného chladícího výkonu pomocí simulace v softwaru BSim 2002. Dále se tento článek zabývá analýzou vlivu nadměrných vnitřních zisků z velkokapacitních vozokomorových pecí na keramiku a implementací provozu těchto pecí do dynamického simulačního procesu. Výsledky této práce ilustrují malý vliv předchlazování pro daný typ objektu a množství nadměrných vnitřních zisků z technologií, a také nedostatek navrženého chladícího výkonu vzhledem k úpravám výrobních postupů ve zkoumané budově.

***Klíčová slova:** dynamická simulace; BSim; průmyslová budova; vnitřní prostředí; komorová pec*

INTRODUCTION

With computer advancements, numerical simulations are quickly becoming an integral part of the design procedure of buildings, building systems and technologies. The numerical simulations allow us not only to evaluate the building energy demands and the internal microclimate but also to study the influences of various design parameters [1]. In this paper, a procedure of the creation and simplification of a building model in BSim 2002 software environment is described with a strong emphasis on the balance between the final accuracy and complexity of the given model. BSim is a software tool to simulate the dynamic behaviour of transient systems, an integrated PC tool is used to analyse buildings and their installations [2]. Furthermore, this paper describes the models' validation using *in situ* measured data in the given building object during a summer period.

The task of this case study was also to examine the possibility of night cooling during the summer period and to investigate its effect on the internal microclimate. The application of building precooling leads to reducing the peak cooling requirements, described in [3]. The major part of the internal gains in the test object is produced by bogie-hearth chamber furnaces. The analysis of these furnaces is also assessed and described in the following study.

BUILDING DESCRIPTION

The examined building is located in Brno in the Czech Republic and serves for purposes of a company engaged in the manufacture, sale and printing of promotional items and gifts together with the related services. There are several printing operations and procedures in the new printing hall and adjacent rooms generating excessive internal gains and odour. The simple situational plan is displayed in Fig. 1 in a satellite view with the highlighted position of the new printing hall and its adjacent buildings. The surrounding of the investigated object is formed by commercial and industrial buildings and by mid-rise apartment buildings.

The old part of the investigated object was built in the 1970s; the big printing hall was constructed in 2008. The external walls of the older part of the printing complex are made of burnt bricks; these walls are not thermally insulated. The internal walls in the older part of the object are made of drywall, panels made of calcium sulphate dihydrate and

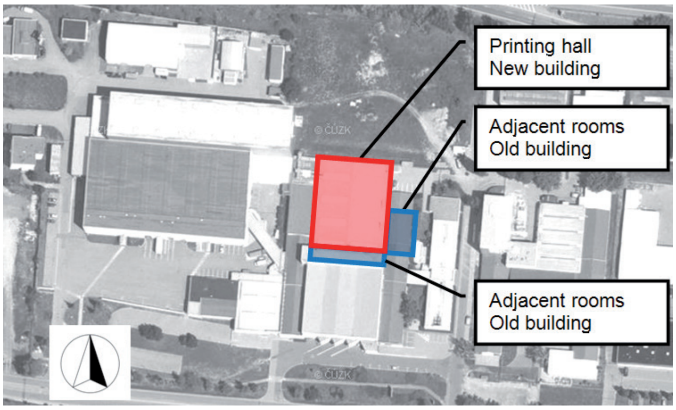

Fig. 1 The examined industrial complex with the location of assessed building objects highlighted

insulated with mineral wool between the panels. The new building is a bigger printing hall with no internal walls between the workplaces with different printing procedures. The external walls in this new part are made of wall sandwich PUR panels (a rigid polyurethane core coated with galvanised sheet metal). Floors in contact with the ground in both the older and the newer part consist of load-bearing concrete, mineral wool insulation and a finishing layer made of PVC. The detailed building compositions used for the BSim computational model are described in Table 1 and 2.

The ventilation and heating of the inspected spaces is provided by one air handling unit placed on the roof of the older object. The heating capacity of this unit is 177 kW according to the technical lists. The only cooling system in the hall is a multi-split air conditioner whose total nominal cooling capacity is 62.0 kW. The operation of all the units is controlled by a BMS (Building Management System). Historical data obtained from the building's BMS were used for the calibration of the heating, ventilation and cooling system in the BSim model.

Tab. 1 The compositions of the building elements in the old building used for the BSim simulation

Structure	Material	Thickness [mm]	Thermal conductivity λ [W/m.K]	Specific heat capacity [J/kg.K]	Bulk density [kg/m^3]
Adjacent rooms (old building)					
Floor structure in contact with the ground	PVC floor	1	0.900	1200	1200
	Concrete	100	1.340	1020	2400
	Mineral wool	0.060	0.039	1310	120
	Concrete	250	1.340	1020	2400
External wall	Brick	300	0.250	900	1900
Internal wall 1	Brick	300	0.800	900	1700
Internal wall 2	Plasterboard	125	0.220	1060	1150
	Mineral wool	175	0.036	800	25
	Plasterboard	125	0.220	1060	1150
Floor structure between the two floors	Concrete	250	1.340	1020	2400
Roof	Thermal insulation + metal sheeting	160	0.042	1370	160

Tab. 2 The compositions of the building elements in the new building used for the BSim simulation

Structure	Material	Thickness [mm]	Thermal conductivity λ [W/m.K]	Specific heat capacity [J/kg.K]	Bulk density [kg/m^3]
Printing hall (new building)					
Floor structure in contact with the ground	PVC floor	1	0.900	1200	1200
	Concrete	100	1.340	1020	2400
	Thermal insulation	160	0.039	1310	120
	Concrete	250	1.340	1020	2400
External wall	PUR panel	120	0.045	1310	112
Roof	Panel roof	160	0.042	1370	160

INDOOR ENVIRONMENT AND HEAT GAINS

The major problems concerning the internal microclimate occurred during the hot summer periods in 2013 and 2014. The indoor temperatures in the hall were reaching values around 30 °C for longer periods of time and occasionally even above 35 °C with a low relative humidity around 25%. Such high temperatures during the work shifts are in conflict with both European [4] and Czech [5] legislation. Moreover, due to the printing machinery, techniques and technologies, the desired relative humidity for the hall is 45%. There was also a problem with the excessive inconvenient odour from the used technologies in the investigated building object.

A significant part of the heat gains in the buildings serving the printing industry purposes are heat gains from technologies [6]. Overheating of the building was observed during the full working load in the summer period, especially in the part of the printing hall where the bogie-hearth chamber furnaces were located. The values of the heat gains from the installed technologies were determined; the bogie-hearth chamber furnaces were measured *in situ* and further analysed in order to more exactly specify their work cycles and thermal loads.

THERMAL LOADS OF CHAMBER FURNACES

There are 3 more powerful bogie-hearth chamber furnaces with forced circulation of the internal atmosphere installed in the printing hall together with two smaller furnaces. These furnaces are used for various types of heat treatment of large batches at temperatures up to 850 °C. The electrical input of each of the more powerful chamber furnaces is 45 kW.

A decisive criterion for determining the maximum furnace heat production into the hall space is the ceramic firing process. The work cycle of each of the pumps is divided into 4 phases: warming up of the furnace and ceramics until the temperature reaches 450 °C, the maintaining phase, the burning phase with a temperature up to 850 °C and a cooling phase of both kiln and ceramics. At the end of the warming up phase and the burning phase, a major part of the thermal load is ventilated into the exterior by an independent air handling unit.

Long-term measurements and observations of the electrical consumption, the temperatures in the furnace during the individual phases and airflows in the ventilation ducts were conducted over the years 2014 and 2015. Furthermore, we carried out the short-term *in situ* measurements of the temperatures above the ceramic products during the last phase when the furnace is open and the ceramic products are cooled down in the open space of the printing hall. The simplified diagram of the work cycle with the rates of heat flow from the furnace is displayed in Fig. 2.

The average thermal production of each of the two most powerful bogie-hearth chamber furnaces is 9.8 kW and the smaller chamber furnace is 7.7 kW. In the case of calculating the heat load discharge by the forced ventilation, the calculation heat load of the more powerful furnaces was determined by a time average to 6.5 kW and the smaller furnace to 5.1 kW. These average heat loads must be included with 100% simultaneity into the total heat load of the hall.

The obtained values of heat flows acquired from the long-term and short-term measurements and the subsequent analysis of the work cycle of the chamber furnaces were used for configuring the internal loads in the BSim simulation. The average calculated thermal load per cycle was used as the equipment load in the BSim simulation. The time schedule of this load was configured according to the real historical utilisation data of these furnaces in the hall.

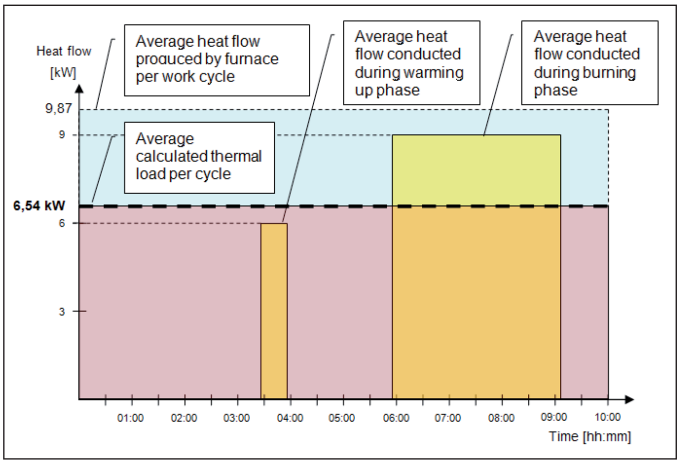

Fig. 2 Diagram of the heat flows from the furnace during the work cycle

CALCULATION METHODS

Simulations were carried out in the software BSim 2002. BSim is based on the law of conservation of energy and the law of conservation of mass with calculations solved non-stationary. Heat is described by the equations of heat balance, using the heat balance formula balanced for the zone:

$$\Phi_{constr} + \Phi_{wind} + \Phi_{sol} + \Phi_{sys} + \Phi_{vent} + \Phi_{inf} + \Phi_{mix} = 0$$

where Φ_{constr} represents the heat flows from the adjoining constructions, Φ_{wind} symbolises the heat flows through the windows, Φ_{sol} is the solar radiation through the windows, Φ_{sys} is the heat flows from the air penetration from the outdoor air (infiltration, venting), Φ_{vent} is the heat flows from the air supplied from the ventilation systems, Φ_{inf} stands for the the heat flows from air transferred from other zones [7].

GEOMETRICAL AND CALCULATION MODEL

The model created in BSim 2002 was created following the main building characteristics and the boundary conditions using the SimView graphic user interface. The geometrical model of the industrial hall and adjacent room is shown below in Fig. 3. The detailed geometrical model of the roof skylights in the printing hall was implemented due to their large area in size and the large amount of solar gains through these opening anticipated prior to the simulation (see Fig. 4).

Fifty time-steps per hour and a Petersen solar radiation model were selected for the simulation due to the complexity of the model and the building construction properties.

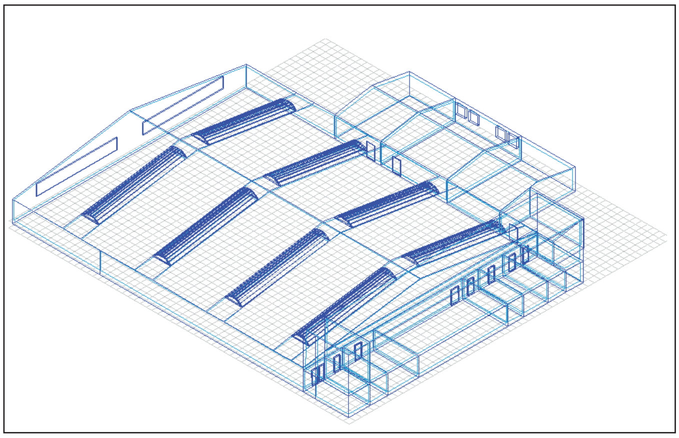

Fig. 3 The geometrical model of the flat and adjacent rooms in BSim

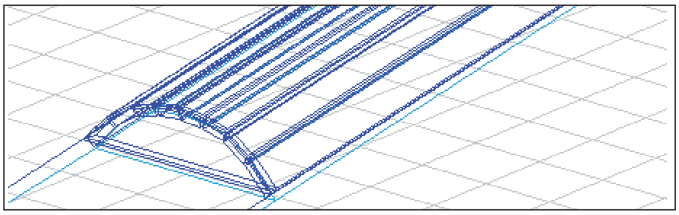

Fig. 4 The geometrical model of the roof skylights

Real weather data continuously collected by a weather station located at the Brno airport were used; therefore, the model can be validated by this data to create the calculation model as exact as possible.

CALIBRATION

First, BSim was calibrated to comply with the room air temperatures measured *in situ* in the printing hall during November and December 2014. The calibration was carried out by changing the amount of exfiltration/infiltration into the exterior. The value of the infiltration is configured in BSim by setting the value of the basic air change [/h]. For the BSim simulation, we have tested the infiltration for the following values of basic air change: 0.1, 0.2, 0.3 and 0.4. The data presented in Fig. 5 represents the room temperature difference (the real measured temperature minus the simulated temperature values) for the values of the basic air change in hour time steps during the inspected period. According to Shapiro-Wilk normality test, the KS normality test and the D'Agostino and the Pearson omnibus normality test, the data of the temperature difference does not evince Gaussian distribution; therefore, the median was used as a decisive statistical factor.

The model with the basic air change 0.2 was used as a reference model for the summer simulation (from the 1st of June 2014 to the 31st of August 2014). The effect of precooling of the building was examined and the cooling capacity of the current cooling system was assessed.

We made simulations of two different methods of operating the building. The first method is the current state: the building heating and also a cooling system which is in operation only during the work shifts and one hour prior the first morning work shift (the first morning shift begins at 6:00) every day during the working days to ensure the internal microclimate conditions meeting the requirements of the Czech and European legislation. The other method of operating the building in-

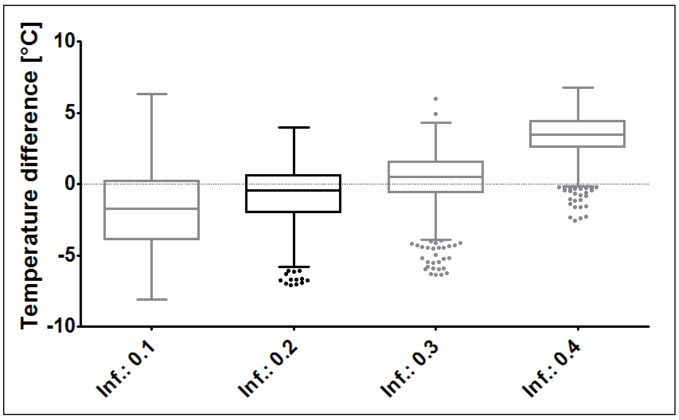

Fig. 5 Configuration of the BSim models using different values of basic air change [/h] – Tukey box plots with a band inside the box representing the second quartile (median)

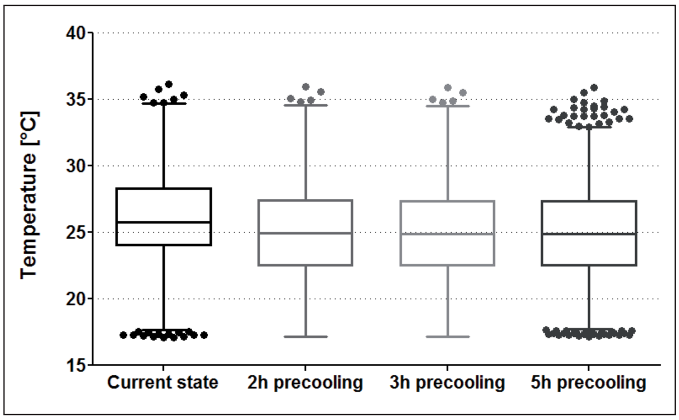

Fig. 6 Box plot displaying the variation in average room temperature samples with different precooling time periods

cludes the night precooling of the printing hall with the multi-split air conditioners and night ventilation prior to the beginning of the morning work shift to 18 °C. The heating and cooling set points were configured to 18 °C and 26 °C, respectively, according to the work classes IIa and IIb given by the Czech legislation [4]. The effect of the precooling of the printing hall was simulated with a different time period before the beginning of the morning work shifts.

RESULTS

The Tukey box plot in Fig. 6 graphically depicts the sample of the hourly average room air temperatures over the inspected summer period during work hours (workdays from 6:00 to 22:00) with different settings of the precooling of the printing hall.

The results from our simulations show a minor difference for each cooling schedule model. In case of the current state, the room's air temperature above 28 °C occurs for 310 hours in the printing hall during the simulated summer time period, requiring 227 hours for cooling turned on 2 hours before the start of the morning shifts, 223 hours cooling turned on 3 hours prior the start of the morning shifts and 223 hours for a 5 hour-long precooling. The simulated hourly room air temperature averages during the working days in July and August 2014 are displayed in Fig. 7.

The second part of this study deals with the simulation of the printing hall with unlimited cooling power to determine the required power of the building's cooling system. The resulting minimal required cooling power gained from the BSim simulation is 326 kW for the summer period 2014, therefore, the required capacity is about 5 times higher than the installed capacity of the current multi-split air conditioners.

DISCUSSION AND SUMMARY

This paper is aimed at the creation of a geometrical and calculation model in BSim in order to investigate the precooling possibilities in the industrial hall and to determine the required cooling power. The industrial hall – printing hall – is constantly overheated during the summer periods with temperatures reaching values around 30 °C for longer periods of time and occasionally even above 35 °C. The large part of the thermal load is generated by 3 bigger and 2 smaller bogie-hearth chamber furnaces. The simulation results of the precooling demonstrate the low improvement of the internal microclimate in the printing hall. It is caused primarily by the excessive instant internal thermal loads during the working shifts in combination with extensive solar gains through the roof skylights and the impossibility of the current cooling system to react to these heat gains due to the insufficient cooling capacity.

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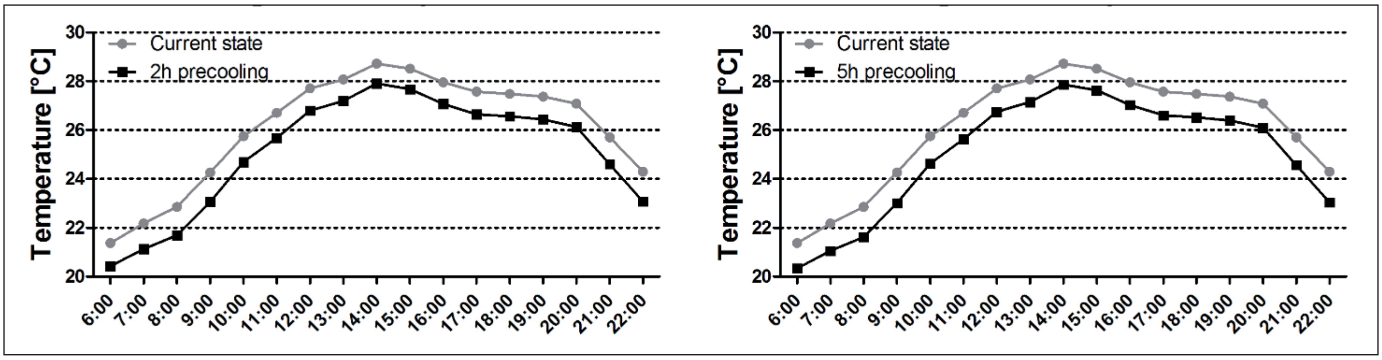

Fig. 7 The hourly room air temperature averages in the printing hall in July and August 2014 for a precooling start 2 hours and 5 hours prior to the morning shift