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A MODEL OF INFILTRATING AIR FLOW AND ITS DISTRIBUTION IN A ROOM WITH A DOUBLE SKIN FAÇADE

MODEL DYSTRYBUCJI POWIETRZA INFILTRUJĄCEGO DO BUDYNKU PRZEZ FASADĘ DWUPOWŁOKOWĄ

Abstract

In the paper, the authors analyzed the impact of space and time discretization on the simulation results of air flow through the double skin façade and its distribution in the adjacent zone. Temperature and air flow in the different parts of the room were considered, taking into account the influence of changeable solar irradiation and wind speed. The calculations additionally took into account: geometry of the zone and its position in the building; weather conditions; façade orientation relative to the cardinal directions; size and types of ventilation components in the network flow.

Keywords: *double skin façades*, *air flow*, *natural ventilation*, *solar energy conversion*, *simulation*

Streszczenie

W artykule przeanalizowano wpływ dyskretyzacji w przestrzeni i czasie na wyniki obliczeń przepływu powietrza przez fasadę budynku i jego dystrybucji w pomieszczeniu. Rozważano parametry termiczne w poszczególnych fragmentach pomieszczenia z uwzględnieniem oddziaływania promieniowania słonecznego i przepływu powietrza o różnych stopniach intensywności. W obliczeniach uwzględniono dodatkowo: geometrię pomieszczenia oraz jego umiejscowienie w budynku, warunki pogodowe, orientację elewacji względem głównych kierunków geograficznych, a także wielkość i metodę definiowania otworów wentylacyjnych w sieci przepływów.

Słowa kluczowe: *fasady podwójne*, *przepływ powietrza*, *wentylacja naturalna*, *konwersja fototermiczna*, *symulacja*

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1. Introduction

In engineering practice, there are many cases in which the complexity of the physical phenomena of construction and their thermal inertia have a significant impact on building assessment methods, which requires the use of advanced computational techniques. Methods based on numerical solutions of physical processes occurring at the boundary of the building and the external environment, generate results burdened with relatively low errors when the problem is properly defined with regard to both space and time. For building components exposed to the intense impact of the external environment, with no doubt, all the elements exposed to solar radiation and wind pressure can be included, in particular, highly glazed and ventilated building envelopes. One of the practical solutions of this type of components are Double Skin Façade systems (DSF). Those are the systems in which the specificity of transient phenomena is just as important as the long-term effects.

The paper presents a short description of the different approaches to space discretization by the Air-Flow Network (AFN) method in space and time. AFN was applied for simulations of heat and mass transfer in the naturally ventilated office room with Double Skin Façade (DSF) applied on the certain percentage of external envelope. For the purpose of research, the computational system ESP-r was employed. It is an integrated energy modelling tool for the simulation of thermal and visual performance of buildings and energy use. The system is equipped to model heat, air and electrical power flows at a user determined resolution. Systematics of selected types of models is outlined in the next section of the paper together with a brief explanation of air-flow network modelling techniques. All simulations were performed using a Polish weather data set prepared for the city of Lodz [1]. The total value of flow rate and air velocity between components was calculated with the time step amounting to 5 or 60 minutes.

Finally, sample results representing the effect of natural ventilation, with the air stream passing through the buffer zone of the façade, during the selected one-month period is discussed. Based on the obtained results, it was found that variation in the vertical/horizontal cross-section of the zone does not generate measurable differences in the context of the volume flow rate counted for comparable connections in the AFN. However, the division of the zone allows for the estimation of the gradation of the internal zone temperature. These results show potential for the further use of AFN in the thermophysical analysis without the necessity for the implementation of time consuming CFD techniques. What should be emphasized and was revealed in the results is that the simulation of air-flow through large openings between thermal zones can act as an oscillating flow. This situation is caused by a simulation engine which re-evaluates conditions at fixed intervals, while in the real world, the flow continually adapts in the whole zone and endeavors to self-balance under changing conditions.

2. Methods

A lot of experimental and numerical analysis has been conducted up til now for the DFS system. Air flow through the façade was analyzed numerically by both: Manz & Frank [2] and Safer et al [3] to investigate strategies leading to a reduction of the overheating during summer and winter. Additionally, combining DSF with HVAC systems was assessed numerically and experimentally by Stec & Paassen [4]. All the main strategies to optimize the energy efficiency of DSF were summarized by Saelens et al. [5].

According to the commonly accepted classification [6], DSFs may be divided into different categories. For the purpose of analysis, a single-storey and partially glazed type of façade was applied. The proposed air curtain system with operable openings improves the thermal insulation of the transparent part of building envelope during the absence of sunlight, especially in the heating season – when the openings tend to be closed for most of the time (Fig. 1a–c). During exposition of the intense solar irradiation in the cooling season (Fig. 1d–f) the DSF is considered as a 'solar chimney', extracting air from the cavity through openings in the skins (inlets and outlets tend to be opened at that time) [7]. The driving force of air movement in the cavity is natural ventilation induced by a combination of the stack effect and the wind pressure distribution at the external skin. The intensity of the air flow in the cavity increases when ventilation in the façade is combined with natural or mechanical ventilation in the zone.

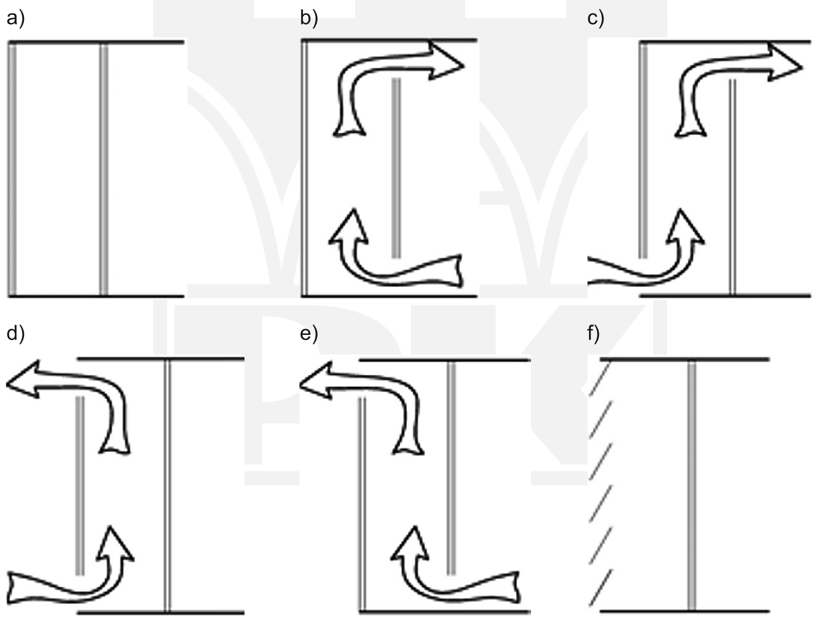

Fig. 1. Distinguish between DSFs due to method of air exchanged between the zone, the adjacent facade and the external environment

Modelling of thermal phenomena for the dynamic simulation of buildings requires the proper numerical description of the particular partitions and of the fluid flow. In the presented approach, all of the components are defined by the nodes representing the volume of solids or the volume of air and the associated heat capacities [8]. The thermal model is based on the finite-volume discretization heat balance method, in which elements of the building structure, zones and associated systems are represented via nodes. Energy balance calculations are made individually for each node. Exchange of heat flux between the nodes, including conduction, convection and radiation (short and long term) is determined on the basis of the solutions of differential equations in space and time. Effects of solar radiation are taken into account in the analysis by the use of instantaneous distribution of the direct radiation, associated to scattered radiation distribution. The system of equations is solved simultaneously to keep the transient thermal equilibrium at each node, including the exchange of energy between them.

In order to determine appropriate coupling phenomena regarding heat and mass transfer, the Air Flow Network method was used. In the AFN method, zones are represented by the patterns of nodal network flow, wherein zones (nodes) with different physical parameters are linked by a flow path and remain in thermodynamic equilibrium. The network connection is described by a number of simultaneously solved nonlinear differential equations that represent the characteristics and form of the flow. Zone models vary in complexity ranging from single zone approximations of entire objects, to complex multi-zone models. Regardless of the model complexity, the flow rate through each connection proceeds with the following assumption: the amount of air flowing in and out of each zone remains at equilibrium (in accordance with the principle of mass conservation).

3. Case study

The first part of analysis was devoted to the sensitivity studies of the model under weather data set, type WYEC2 (Weather Year for Energy Calculation, Version 2) developed for the city of Lodz [1]. The same weather data set was used for the remaining simulations. The preliminary study was carried out for the whole calendar year, with a 1 hour time step, to search for appropriate volume flow rate. This volume should provide healthy indoor parameters for a 3 office user. Minimal flow rate was set to 20 m^3/h per person. The sensitivity studies were performed for case the described in Fig. 2a). The system for heating and cooling was set to maintain indoor temperature in range of 20°C–26°C. 3 persons were assumed to occupy zone from Monday to Friday during office hours (8:00–16:00). According to the number of occupants, the total heat gains were specified to 220 W per person, where 120 W was delivered by the equipment. It was assumed that solar radiation would be a sufficient source of the daylight, therefore, heat gains from artificial lighting were set to zero. Network flow assumes the occurrence of 5 nodes (2 internal and 3 external – boundary with wind induced pressure). The coefficient of pressure distribution was determined for the 2 external nodes located on the façade as well as for semi-exposed walls and for one node representing air outlet (located in the zone) and for a semi-exposed roof with a slope of less than 10 [8]. The flows at nodes are a function of nodal pressures and the connected components' characteristics. Thus, two main features of components were the object of the first part of analysis – the area of opening and discharge coefficient. This two characteristics (yearly and monthly) were set-up in the number of simulations to assure an average volume flow rate at a value of 60 m^3/h for the office zone.

Additionally, it was established that for certain months and air-flow controlling functions, the energy loads for cooling were nearly equal to zero. The heating season persisted from the beginning of October till the end of April. Two months, May and September, were considered as transitional and the month of May was later considered in final analyses with two time steps – 5 or 60 minutes. The month of May was selected due to the fact that in this period, the heating and cooling energy demands are equal to zero (for a well-insulated and properly ventilated zone). The following statement was also proved by the authors in the previous publications [9] – zero energy loads leads to the switching off of the system which maintains assumed minimal and maximal temperatures and further allows air flow to function without disruptions.

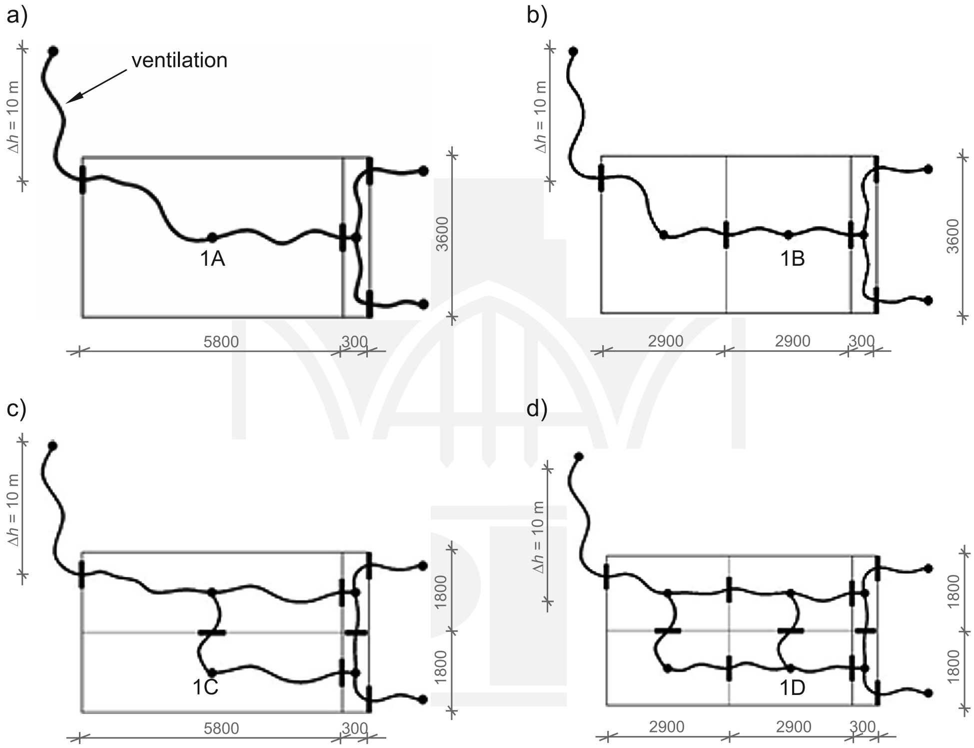

Fig. 2. Overview of analyzed cases: a) two zones Model A, b) three zones Model B with vertical division, c) four zones Model C with horizontal division, d) six zones Model D with mixed horizontal and vertical division

The main part of the analysis was devoted to the assessment of the total value of volume flow rate and air velocity through the ventilation openings extracting the air from the zone (due to impact of different zones' discretization). First, the air-flow was evaluated for the zone and façade without sub-division (Fig. 2a – Model A). In the next step, the internal zone was sub-divided into 2 (Fig. 2b – model B and 2c – Model C) and 4 sub-zones (Fig. 2d – model D) by use of horizontal and vertical partitions. In other words, the number of external nodes remained constant (3 nodes) while the number of internal nodes was set to 2, 3, 4 and 6 (Fig. 2, cases: a, b, c, d).

The influence for heat and mass transfer of internal partitions, located between sub--zones, was neglected due to the special physical properties assigned to these partitions. These partitions were prescribed using a so-called ‘fictitious material’, with the following assumptions: near-zero thermal mass; solar radiation and absorptivity; close unity emissivity; solar radiation penetrates the fictitious surface without major obstacles and changes in intensity of the component factors.

The area of the façade was either modelled as a single zone or divided into two zones and connected via components to create a set of flow paths. Two external nodes were assigned to the inlet and outlet. A single office area was created based on a real zone with dimensions of (depth × width × height) 5.8 m × 3 m × 3.6 m with additionally vertically added façade – given its dimensions of (depth × width × height) 0.3 m × 0.6 m × 3.6 m. The basic material structure of the initial zone was developed based on the assumption of high thermal insulation and a constant heat capacity of the compartments. As the insulating material, rock wool was applied on the internal part of the partition with the thickness equals to 200 mm, regardless of the vertical or horizontal partitions.

Due to the investigated problems of the air flow, a standardized construction of glazing was defined. From the available database of materials, clear float glass was chosen with a thickness of 2 × 6 mm for the internal double glazed unit and 10 mm for the external single glazed unit. Air gap in the double glazed unit was filled with 12 mm of pure air. As was previous mentioned, all condition controlling systems were switched off.

4. Results

The results presented below relate to the month of May and were obtained with 5 or 60 minutes lasting time steps. Figures 3 and 4 show the Volume Flow Rates (VFR) through the zone by ventilation connections (Fig. 2a). Figures 5 and 6 show velocities recorded for the connections between nodes 1A, 1B, 1C and 1D (Fig. 2 a–d) and the nearest nodes located in the cavity of the double skin facade. Additionally, the temperatures of 1A, 1B, 1C and 1D nodes were considered to evaluate potential gradations of this parameter, these are presented on Figs. 7 and 8.

Figs. 3 and 4 show that the differences in the office zone discretization did not generate noticeable errors in the total VFRs for office zone ventilation purposes for each of the analyzed cases. The average VFR value is in each case equal to 0.02 m^3/s. The highest noted value of the volume flow rate reached approx. 0.11 m^3/s. Periodically ‘reverse’ flow was also noted (reverse in relation to the direction of flow, which for natural ventilation means suction of air by the ventilation opening), with the minimal value equal to –0.02 m^3/s. Comparison of Fig. 3 and 4 indicates a lack of significant difference in the results of VFRs recorded for time step of 5 or 60 minutes.

In the future analyses of the office zone, one of the criteria of assessment could be occupant’s comfort. For this reason, the temperature and velocity of air movement in the area of glazing and at the bottom area of the office zone (where users’ desks are usually located) will play an important role. On that basis, nodes 1A, 1B, 1C and 1D were considered for the estimated air velocity and temperature on the nodes. A synthetic glance at Fig. 5 and 6

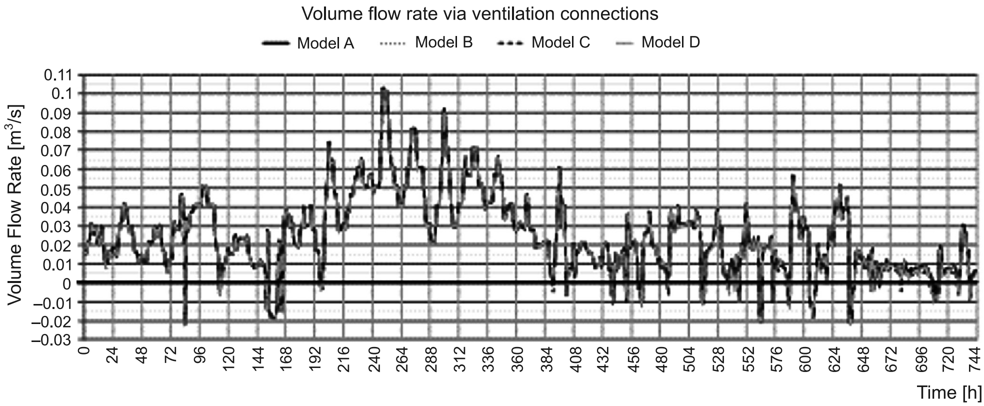

Fig. 3. Volume flow rates through the zone ventilation connections recorded with 60 min. time step

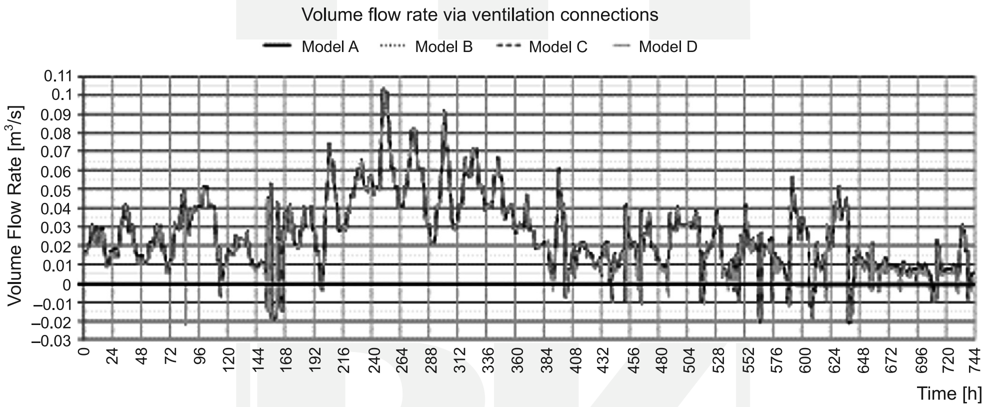

Fig. 4. Volume flow rates through the zone ventilation connections recorded with 5 min. time step

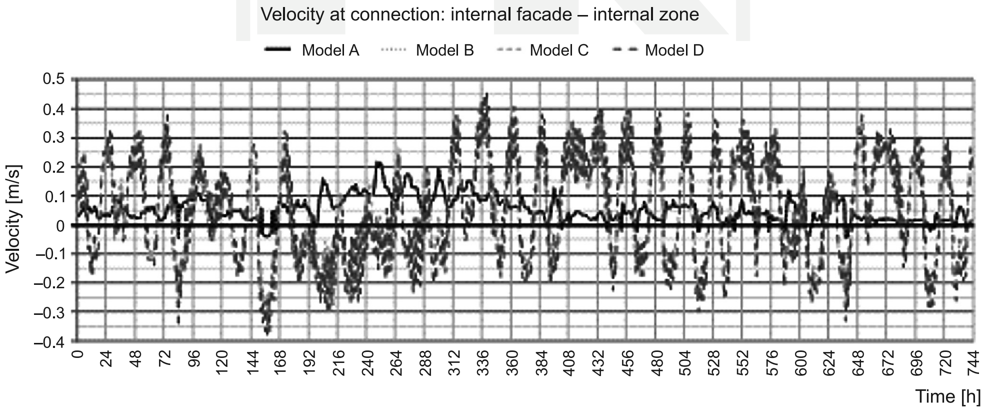

Fig. 5. Velocities at the connections between nodes 1A, 1B, 1C and 1D (see Fig. 1 a–d) and the corresponding façade nodes recorded with 60 min. time step

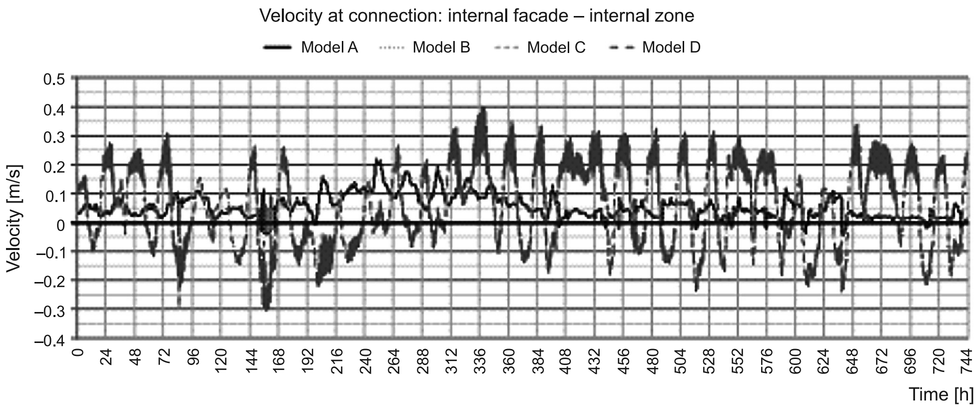

Fig. 6. Velocities at the connections between nodes 1A, 1B, 1C and 1D (see Fig. 2 a–d) and the corresponding façade nodes recorded with 5 min. time step

allows for a quick description of the results which is as follows. Between velocities recorded for model A and B, there are no divergences in the value. However, due to the fact of the zone division, velocities recorded in the results for Model C and D have greater values than in models A or B. This is the result of separation of the air flow flux from one to two channels. What is also very important, in the results for model C and D, some oscillations at the peaks in the velocities can be observed for both time steps – 5 and 60 minutes.

The velocities in models A and B usually have values greater than 0 m/s (which means that flow is consistent with 'typical' functioning of natural ventilation) while the values of velocities in the models C and D relatively often drops below 0 m/s (which means that flow is contrary to 'typical' functioning of natural ventilation). While in all 4 cases, the average velocity remains at a level of 0.05m/s, the maximum values differ significantly comparing cases A & B to the cases C & D. In models A & B, the max. value of air movement is 0.2 m/s. In models C & D, the maximum value of air movement is 0.4 m/s.

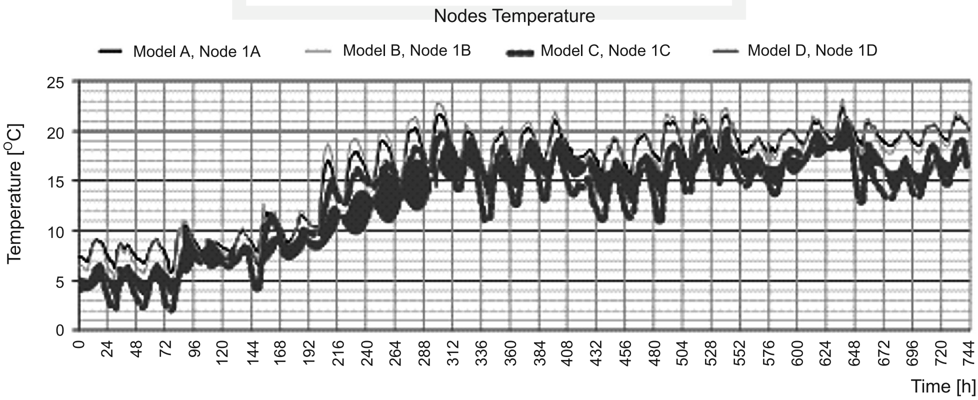

Fig. 7. Temperature of 1A, 1B, 1C and 1D nodes recorded with 60 min. time step

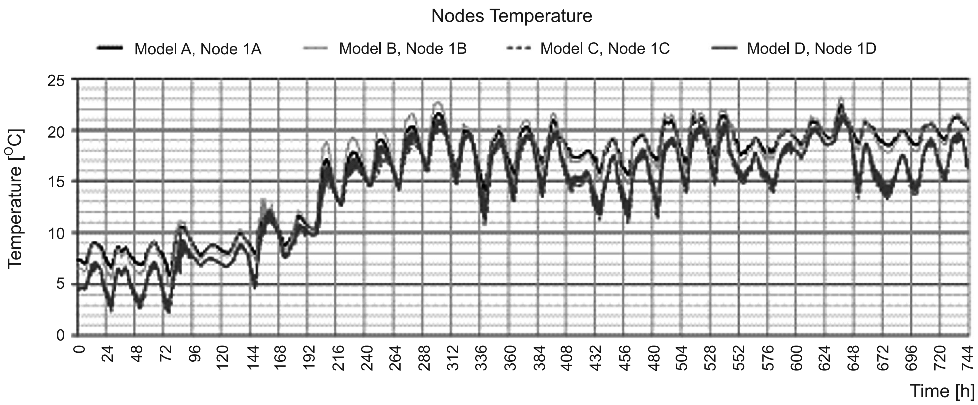

Fig. 8. Temperature of 1A, 1B, 1C and 1D nodes recorded with 5 min. time step

Similarly, in relation to the oscillations in the velocities considered above, the situation is observed for the temperatures of nodes 1A, 1B, 1C and 1D, presented in Figures 7 and 8. In the case of temperatures however, much higher oscillations occurred for the 60 minutes time step results. The greatest oscillations were noticed for the fluctuation of the temperature for node 1D, in model D, computed with a 60 minutes time step. For the 5 minutes time step, these oscillations were significantly lower for the same case. Also, noticeable differences are recorded due to the different locations of the considered nodes. The highest temperature was recorded for node 1B in Model B, and the lowest temperatures for node 1D, in model D.

5. Result analyses and discussion

On the basis of the presented results, the following conclusions can be drawn. The method of discretization of office zone in time and space does not significantly affect the volume of air flow through the ventilation. For all four models, the average value of the flow rate through the zone was approximately 0.02 m^3/s, which corresponds to 72 m^3/h. This value satisfies the requirements to ensure hygienic conditions for the office users. However, it is also highly variable and depends on the boundary conditions, namely wind speed pressure distribution at the external nodes. In extreme cases, the flow rate can reach values of up to 0.1 m^3/s, which corresponds to approx. 360 m^3/h and far exceeds the expected value. In the other recorded cases, natural ventilation performs as air supply instead of air exhaust, what is not a preferred phenomenon because of accumulated in chimneys dirt and sediments.

Due to the assessment of user comfort and, associated with these analyses, the air flow velocities and temperature of the selected nodes, the results prompt caution. An obvious phenomenon is the appearance of a different distribution of air flow velocities and temperature of the nodes – the authors raised no less concern towards the revealed oscillations observed for certain parameters of selected nodes. It turns out that the errors of numerical solutions grow dramatically when the network flow goes through the large openings, leading to oscillation in the range of 8%–15% for the 5 and 60 minutes time step respectively. It is therefore recommended in the literature [9], and was confirmed by the results presented on the Figures 7 and 8, that the simulation of the network flow through the large openings should be done using a time step no longer than one minute. This will allow for the estimation of results with an error decease within the range of 1%–2%.

The conducted simulations lead to the conclusion that in order to obtain the most reliable and accurate results, simulation models should be designed accurately. Formation of the proper air flow network, constructed from the optimal number of nodes and their correct distribution, has the most significant influence on the results.

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