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Research Article

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Predicting natural ventilation flows in whole buildings. Part 1: The Viipuri Library

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Abstract

For energy efficient restoration of historical buildings, especially historic monuments of international importance such as the Viipuri Library by Alvar Aalto (1898 – 1976), new analytical tools are needed. Of interest to this research is the evaluation of air movement within this building due to spatial composition, which can also prove very useful in helping architects determine how best to renovate and restore historical buildings. The objective is to analyze how radiant heating and passive cooling are currently exploited in the Viipuri Library. The knowledge will be useful to restore this historical building to function efficiently while ensuring that the existing mechanical ventilation systems and natural convective flows work well together after restoration. Computational fluid dynamics will be used to model, simulate and predict multiple environmental conditions to examine spatial layout effects on the ability of natural ventilation to maintain a comfortable thermal environment and acceptable rates of ventilation. The preliminary results demonstrate that airflow and thermal effects can be predicted and validated for any set of conditions, such as specifying which windows or doors are open, and the ambient conditions exterior (e.g., wind and air temperature) and interior (e.g., radiant pipes) to the building.

Keywords

computational fluid dynamics,
energy efficiency,
free flow open space,
natural ventilation,
restoration

Article History

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1 Introduction

The restoration of historical buildings, especially historic monuments of international importance, is generally a complex endeavor as many parameters need to be considered by preservation architects and engineers. Complexity is even larger when issues of energy efficiency and sustainability are added tasks and concerns, for example, when new systems for heating, cooling and ventilation need to be installed due to changed user needs, updated building codes or other issues related to adapting a historic building for contemporary use.

One building of particular interest is the municipal library in Vyborg, Russia (The original name of the town and the library was Viipuri during the Finnish rule, and today is called Vyborg.), designed by the Finnish architect Alvar Aalto in 1927 and built in 1935. The library was built with an innovative mechanical ventilation system that failed to function due to war damage. At that time, the implementation of mechanical heating, cooling and ventilation systems in buildings was still at its infancy, thus it is not clear if the library's system ever functioned properly. The library was designed with thick exterior masonry walls in which ventilation ducts were embedded as well as a hydronic radiant heating system in the various ceilings. The air ducts were fairly narrow and air was supposed to enter through inlets near the ceilings and exhaust through outlets above the book shelves. Ever since the library's first restoration in the mid-1950s, natural ventilation was exploited to condition the building in addition to its innovative radiant ceiling system. More recently, the restoration of the mechanical ventilation in the ongoing restoration process is a major concern (Karjalainen 2009).

In our efforts to evaluate the energy efficiency of the Viipuri library, we consider how best to condition the air in the building. One method to conserve energy in the conditioning of buildings is the use of natural ventilation, which takes advantage of natural airflow through a building to moderate thermal comfort. The natural airflow can be

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introduced due to wind around the building or natural convection caused by thermal gradients within the building or between the building and the atmosphere. In buildings designed to exploit natural ventilation, air must be able to flow freely through the building. Spatial layout, the idea of how different areas of a building connect, is very important when considering flow through a building. Architects describe free flow open spaces as volumes of horizontal and vertical spatial continuity (Passe 2008). These volumes (or regions) within a building are connected by wall apertures, passageways, stairways, split levels, interior windows, or double height spaces (Passe et al. 2008). How exactly the shape and location of these connections affect airflow in three dimensions is the broader research question.

The governing equations to describe the physical phenomena of fluid dynamics and heat transfer are broadly acknowledged in building science literature (Allard and Ghiaus 2005) and the basic concepts are shown with diagrams and two-dimensional arrows (Fathy 1986; Brown and DeKay 2001). However, predictions of the interrelationship of the connecting spaces and airflow patterns, for example, the Venturi-effect, buoyancy effects, and cross ventilation in relationship to thermal patterns, are only integrated intuitively into most designs (Kwok and Gronkzik 1999). As Chen (2004) points out, airflow patterns predicted by the architect often vary greatly from the actual airflow through the building.

Thus far, architectural research addresses the energy use of heating and cooling mostly through optimization of mechanical systems and the building envelope. The use of spatial design to reduce energy consumption by exploiting convection is not quantified in the energy performance evaluation of buildings, yet. The phenomenon of air temperature stratification has only recently been examined for parts of buildings, like double skin facades or atria (Göcer et al. 2006; Omri and Galanis 2010). The energy needs or savings relative to spatial construction have not been sufficiently examined or considered. Usually building spaces are equipped with heating, ventilating and air-conditioning (HVAC) systems after design decisions have been made. More appropriately, energy requirements for these HVAC systems should be integrated into the design process. The impact of volumetric composition on the flow of energy is critical, and both architects and engineers need to change their approaches and work as a synergistic team to produce buildings that are both aesthetic and energy efficient.

Simulating whole buildings to analyze the airflow pattern is a novel approach that will be demonstrated in this paper using computational fluid dynamics (CFD). Energy transfer will be predicted by modeling a building in three dimensions, including windows, vents, etc., to provide a true interpretation of how building design and spatial layout affect thermal energy distribution. We use CFD in this study is to demonstrate its potential application as a design tool. Although CFD simulations still require significant computation time, the utility of CFD can be relatively inexpensive to explore options during the design stage as compared to making faulty renovations in an existing building under operation.

In this study, the commercial CFD software FLUENT will be used to model airflow and temperature fields in the Viipuri library, and to examine the effectiveness of natural ventilation to control thermal comfort. Both radiant heating and passive cooling will be examined using multiple environmental conditions. CFD simulations will examine spatial layout effects on the ability of natural ventilation to maintain a comfortable thermal environment and acceptable rates of ventilation to maintain fresh air throughout the building during different atmospheric conditions. The paper begins with a brief survey and discussion on CFD modeling approaches, followed by the numerical methodology used for the simulations herein. Results are presented for heating and cooling scenarios to compare the effects of the temperature and velocity fields when environmental conditions are changed, with concluding remarks.

2 Background

There has been significant research conducted using numerical techniques to model airflow in and around a single room building (Asfour and Gadi 2007, 2008; Schaelin et al. 1992; Ayad 1999; Heiselberg et al. 2004; Bastide et al. 2006) but few detailed studies of whole buildings. One computational method to analyze building energy usage is the zonal or network model, which has been widely used to simulate airflow and thermal comfort through multi-room buildings. The network model defines each room as a control volume and assumes that the temperature and pressure within a room are uniform (Wang and Chen 2007). Mass and energy balance calculations are performed on the control volume to find temperature and pressure within the zone as well as the mass flow rate at the boundary. The omission of pressure variations within a zone has been shown to provide erroneous results. More recent approaches to zonal modeling divide zones into multiple subzones so that multiple pressures and temperatures can be calculated within a zone (Wang and Chen 2007).

The advantage of CFD modeling is that instead of examining the average temperature in a room, a CFD investigation can identify parts of a room or building that are not cooled or heated sufficiently. While CFD is the more obvious choice for accurate predictions, there are many problems when simulating natural ventilation. Thermally driven flows are usually characterized by low Reynolds numbers with high levels of turbulence caused by buoyant plumes that can create problems with numerical convergence in the simulation (Ji and Cook 2007). In buoyant flows, the ratio of buoyancy forces to viscous forces is defined by the Grashof number, $Gr_L = g\beta(T_S - T_\infty)L^3/\nu^2$, where g is gravity, β is the coefficient of thermal expansion, $T_S - T_\infty$ is a characteristic temperature difference, L is a characteristic length, and ν is the kinematic viscosity (Incropera et al. 2007). The flow regime is determined using the Rayleigh number, $Ra = Gr_L Pr$, where the Prandtl number is $Pr = \nu/\alpha$ and α is the thermal diffusivity. According to Incropera, et al. (2007), buoyancy-driven flows transition from laminar to turbulent flow at $Ra \approx 10^9$.

In a flow that is driven by both buoyancy and pressure gradients, the choice of boundary condition becomes important. Heiselberg et al. (2004) showed that the solution of combined-effect flows is dependent on the relative magnitude of the forces due to buoyancy and pressure. Without knowing which force is dominant, the boundary conditions in combined-effect flows must allow fluid to enter or exit the boundary.

Another issue to be considered when performing CFD simulations for natural ventilation in buildings is the availability of computing resources. Schaelin et al. (1992) used 39 000 cells for simulations of a domain approximately 16 000 m^3. Asfour and Gadi (2008) recently found that using a mesh of 2.25 million cells for a domain of 18 000 m^3 was beyond the capabilities of the computing resources available to the authors. It should be noted that neither study specified the type and number of processors or amount of memory available for the simulations. Therefore, discretizing whole buildings is constrained by the available machine memory and processor speed, restricting grid resolution to be too coarse to capture the physics of the flow and necessitating the use of turbulence models.

3 Numerical approach

3.1 Formulation

The commercial software FLUENT 6.3 (2006) was used to perform all simulations. The following briefly presents the equations and models employed. Conservation of mass is given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

where ρ is the fluid density and $\vec{v}$ is the velocity vector. Conservation of momentum is given by

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} \tag{2}$$

where p is pressure, $\bar{\bar{\tau}}$ is the stress tensor for a Newtonian fluid, and $\vec{g}$ is the gravitational body force vector. For the current study, the flow is considered incompressible because low velocities and small pressure differences are present in the domain.

The Boussinesq approximation is used and assumes that density differences are small except for the buoyancy force, which is due to vertical density gradients and the gravitational force. Thus, the thermal expansion coefficient β can be approximated as (Kays et al. 2005):

$$\rho_0 - \rho = -\rho_0 \beta (T - T_0) \tag{3}$$

where ρ_0 and T_0 are reference values. Equation (3) can be solved for the variable density ρ and substituted into the term ρg of Eq. (2). All other density terms are replaced with ρ_0.

The general form of the energy equation is given by

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot [\vec{v}(\rho E + p)] = \nabla \cdot k_{\text{eff}} \nabla T + \nabla \cdot (\bar{\bar{\tau}}_{\text{eff}} \cdot \vec{v}) \tag{4}$$

where E is total energy. The effective conductivity, k_{eff}, is the sum of the fluid thermal conductivity and the turbulent thermal conductivity. The second term on the right hand side represents viscous heating; however, this value is neglected for most incompressible flows.

The standard k-ε turbulence equations were used to model free stream wind, which is inherently turbulent (Asfour and Gadi 2007). Two additional transport equations to calculate the turbulent kinetic energy, k, and the turbulent dissipation rate, ε, are given by

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \vec{v}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k + G_b - \rho\varepsilon + S_k \tag{5}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \varepsilon \vec{v}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + C_{1\varepsilon}\frac{\varepsilon}{d}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{6}$$

where G_k is turbulent kinetic energy production due to mean velocity gradients; G_b is turbulent kinetic energy production due to buoyancy; S_k and S_ε are source terms; σ_k and σ_ε are turbulent Prandtl numbers; and μ_t is the turbulent viscosity. The constants $C_{1\varepsilon} = 1.44$ and $C_{2\varepsilon} = 1.92$, have been determined to work for a wide range of flows (Launder and Spalding 1972, 1974). The effects of the buoyancy generation term are considered negligible; therefore $C_{3\varepsilon}$ is set to zero. Further details of the formulation can be found in (Fluent 2006).

FLUENT uses a control volume approach to calculate the dependent variables at the center of each cell. A second-order upwind discretization scheme for the spatial terms was employed to compute variables at the cell face using the cell-centered data. In addition, the SIMPLE algorithm (Patankar and Spalding 1972) was used for pressure-velocity coupling. Both first- and second-order explicit time discretization schemes were tested and it was found that first-order accuracy was sufficient, thus reducing the computational time necessary for a converged solution at each time step.

There are three boundary types used in the study: surfaces, inlets and outlets, which represent openings within the building. At inlets, a uniform velocity profile, with both speed and direction, and the temperature of the incoming air are specified; for each case, conditions are used to represent weather patterns for a particular season and will be discussed further. At outlets, the ambient air pressure and temperature are specified to account for conditions outdoors. All surfaces that represent a wall assume the standard no-slip condition for fluid-surface interaction (White 2003). The thermal boundary conditions at the wall are set to either adiabatic, uniform temperature or uniform heat flux, and have been used in other studies (Rundle et al. 2011). Heat transfer by conduction through walls is not modeled for this initial study because of the increased computational time; herein, the focus is to assess airflow in relation to the spatial layout of the building. The specific conditions will be discussed for each case.

3.2 Grid resolution study

A grid independence study was performed to determine an acceptable grid resolution to use for natural ventilation simulations. The study of Schaelin et al. (1992) was used to validate the grid resolution, which was a numerical study based on the experimental work of Mahajan (1987). The domain used in the simulations is presented in Fig. 1 for a single room building open to the atmosphere on the left side by a door located at $x = 0$ that extends vertically for 2.2 m. Heat is provided to the room by a heater opposite to the door. The exterior boundaries that simulate the atmosphere are set to zero gage pressure and ambient temperature ($T_{\mathrm{amb}} = 20^{\circ}\mathrm{C}$).

Three grid resolutions with uniform spacing of square cells with 5, 10, and 15 cm per side were tested. The velocity through the door in the horizontal direction is compared to results given by Schaelin et al. (1992) and shown in Fig. 2. Increasing the grid resolution by reducing the cell size improved the results overall and serves as a guide for determining the grid resolution for the full-scaled building of the library. The complex geometry of the Viipuri Library was initially discretized into unstructured cells with a length of approximately 10 cm; however, the total number of cells required exceeded the computer memory. Therefore, it was necessary to vary the node spacing throughout the building, with the smallest cell dimension of approximately 20 cm and the largest dimension of 50 cm. The total number of cells used to discretize the Viipuri Library was about 750 000. Further details related to convergence criteria are discussed in the following sections and summarized in Table 1.

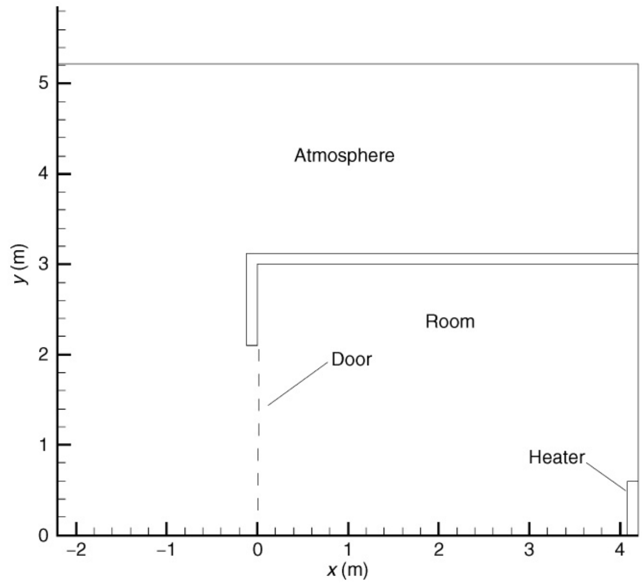

Fig. 1 Computational domain for grid independence study

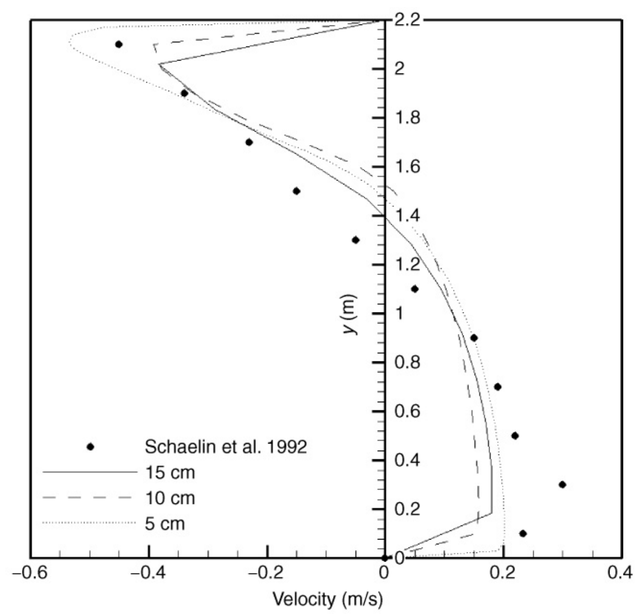

Fig. 2 Velocity profile at door for grid resolution study with cells widths of 5, 10 and 15 cm

Table 1 Summary of cell size, time steps, and CPU

	Heating	Cooling
Total # cells	750 000	
Min cell size (cm)	20	
Max cell size (cm)	50	
Δt (s)	0.25	0.1
CFL	1	0.5
# Pseudo-iterations	127 000	625 000
t_{max} (min)	60	20
CPU time (h)	151	110

CFL: Courant-Friedrichs-Levy number.

4 Results and discussion

4.1 Building layout

When exploiting natural ventilation in a building, air velocity must be considered as a variable for human thermal comfort. The factors for human thermal comfort are judged based on ASHRAE Standard 55-2004 (ASHRAE 2004). For buildings without significant air movement, ASHRAE recommends temperatures within 20 – 25℃ provided that the maximum velocities do not exceed 0.2 m/s. However, if natural ventilation induces higher air speeds, the maximum temperature is 28℃ provided that the air velocities do not exceed 0.8 m/s. Other variables for human comfort relative humidity and mean radiant temperature, and clothing have been considered as neutral.

Figure 3(a, b) shows two views of the library, which consists of two large volumes: a smaller volume of offices on the north side and a larger section to the south. The spatial layout of the library can be appreciated by examining the schematic shown in Fig. 4, which shows views without the ceiling. The major features of the library are the split level section and a circular staircase within the lending area in the southern section that allows only the librarians to travel between and observe all three levels. The split level section comprises the lending area (upper level) and reading room (lower level), as shown in Fig. 5; these rooms will be examined in more detail in this study. The northeast section includes the main entrance of the building and to the right is a large lecture hall with an undulating wood ceiling (see Fig. 3(a)). There is a stairwell to the left of the entrance that leads to office space on the second level and a storage area in the basement. From the basement, there is access to the children's library below the reading room, which also has a separate external entrance (see Fig. 3(b)). As a patron walks through the main entrance, there are 8 steps that lead into the stacks of the library. At the top of the stairs, the reading room is to the left and to the right is a staircase connecting the split levels of the stacks and the lending desk (see Fig. 3(a) and Fig. 4). All of the spaces in the larger part of the library are connected and open, allowing air to flow easily between the sections (see Fig. 4 and Fig. 5).

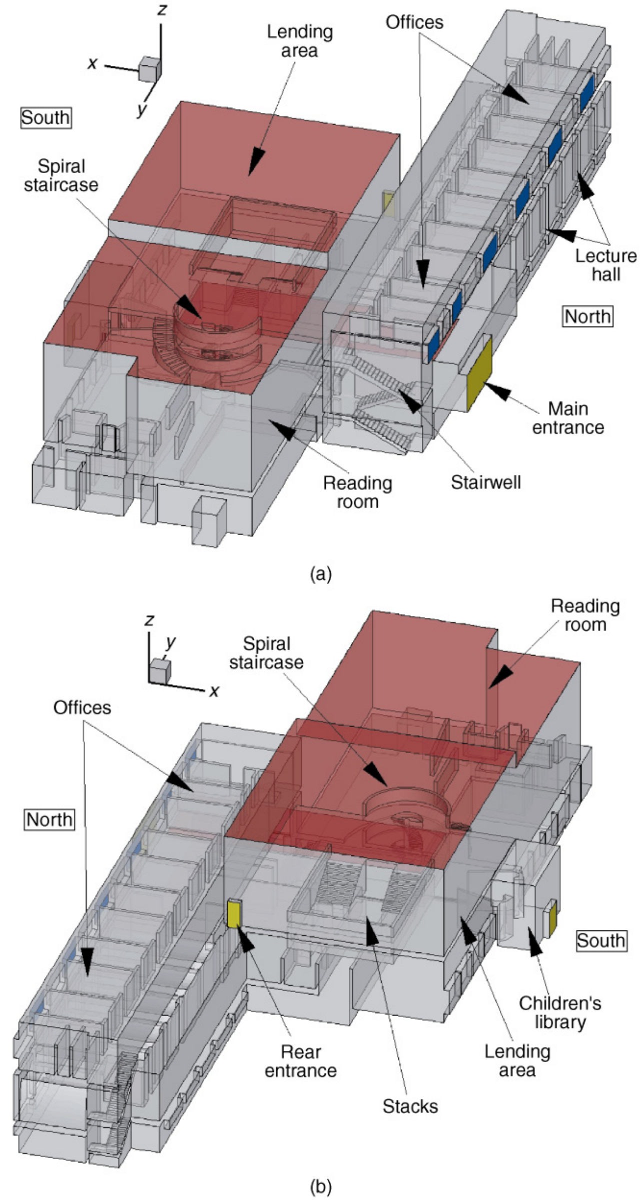

Fig. 3 Views of the Viipuri Library. Red—heated ceiling; yellow—door; blue—window

Heating in the building is provided by hot pipes in the three sections of the ceiling, shown as red surfaces in Fig. 3. Normally the front (main entrance) and rear doors are kept open to increase airflow through the building as well as regulate temperature during the summer (yellow surfaces in Fig. 3). In the present study, a third door located in the children's library is opened and is also shown in yellow. Windows located in the office space on the second level of

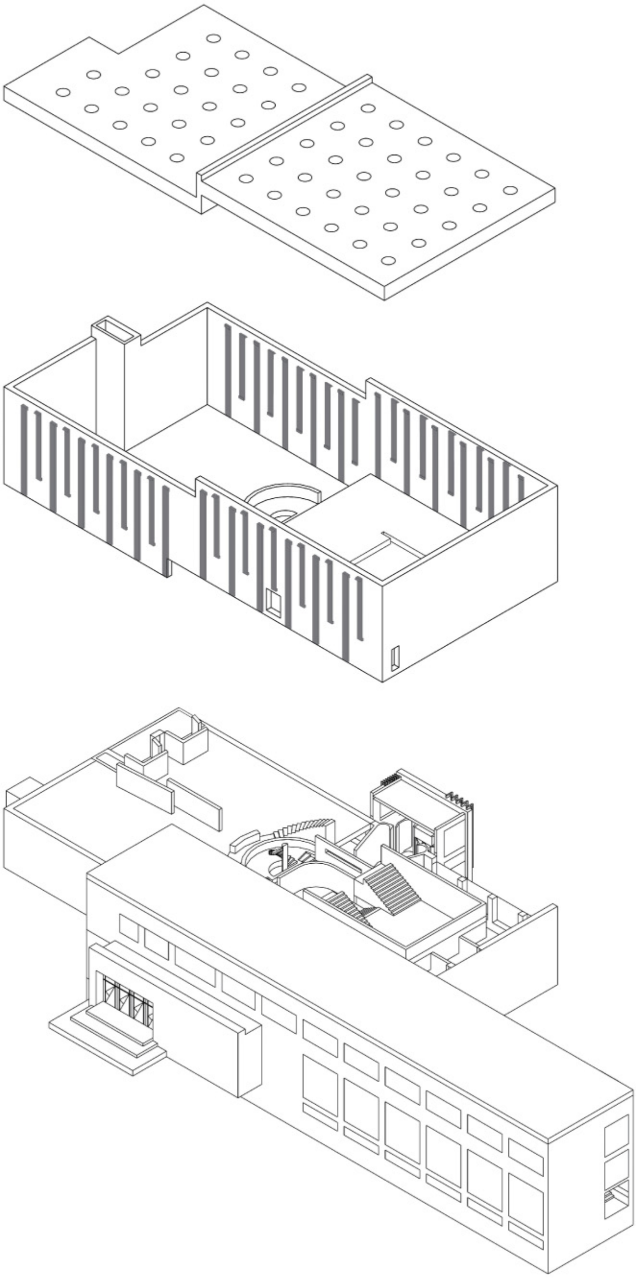

Fig. 4 Schematic of an exploded view of the library

the shorter section can be opened to allow more airflow through the building (shown in blue in Fig. 3(a)). The lecture hall is lined with windows that cannot be opened but provide ample light to the room. From the beginning, this section of the library had a conventional mechanical ventilation system independent from the rest of the library, which had also fallen into disrepair but was restored in 2009. Additional windows located in the children's library allow that area to be lit using natural daylight. Lighting in the lending and reading areas is provided by an array of skylights.

Fig. 5 Photograph of the split level that comprises the lending area (upper level) and the stairs that lead to the reading room (lower level). Photograph was taken during the author's visit to Vyborg

4.2 Radiant heating study

Since the early 1990s, the library has been undergoing major restoration efforts. After the earlier restoration of the newspaper room, entrance hall and lecture hall, the next focus of the restoration in the Viipuri library is within the large reading room and lending area where the radiant hot water pipes provide heating. Recently, radiators under the lecture hall windows have been restored but will not be modeled for these studies. We begin with the heating study to demonstrate how the library currently functions without a central ventilation system. In conjunction with the radiant heat, the front and rear doors of the library are propped open to help circulate airflow to maintain thermal comfort.

A total of three heating simulations were performed. The hot water pipes in the ceiling were modeled as a constant surface temperature of 50℃ and the front entrance allowed air to enter the building. A small slit with air entering at an angle of 45° parallel to the door was used to model a single door being propped open slightly. The rear door was also modeled as a small slit to replicate the door being propped open to allow cross ventilation in the building. The initial temperature T_o of the building for all cases was set to 15℃ with no air movement to represent when the library is first opened for business in the morning. A summary of the boundary conditions used in the heating simulations is provided in Table 2. For all cases, $Ra \approx 10^{12}$, indicating that the airflow is turbulent. The time step used for the transient simulations was 0.25 s; most simulations required around 20 – 30 iterations per time step. The convergence criteria were satisfied when residuals dropped at least three orders of magnitude and the change among all residuals was less

Table 2 Summary of the Viipuri Library heating cases

	Reference Case (§4.2.1)	Reduced atmospheric temperature (§4.2.2)	Main door (§4.2.3)
Open door	Center	Center	Left
v_{atm} (m/s)	4	4	4
T_{atm} (℃)	5	−5	5
$T_{ceiling}$ (℃)	50	50	50
T_o (℃)	15	15	15

than 1%. The heating cases were simulated up to a time of 1 hour and required approximately 150 CPU hours on a dual core processor (3 GHz Xeon 5160) with 2 GB of memory.

4.2.1 *Reference heating case*

The reference heating case specifies atmospheric air entering (T_{in}) through the center door of the main entrance at 4 m/s at an ambient temperature of $T_{atm} = 5$℃. The atmospheric conditions for wind and temperature were selected to replicate a typical morning when the library would open for business during the month of January, based on weather conditions averaged over a 5-year period (NCDC 2011). These conditions were selected in order to understand how well the heating system currently performs to provide thermal comfort prior to the arrival of customers.

Figure 6(a, b) presents air temperature and velocity contours for the flow field after one hour. A small insert in the upper frame shows the entire building with three black lines to identify the *x*-*z* planes shown. The top plane is a section of the reading room and basement, the middle plane bisects the doors of the main entrance and the lending area, and the bottom plane shows a section of the lending area near the back door and includes the lecture hall. Figure 6(a) shows that the air temperature is horizontally stratified throughout all rooms of the building and the air temperature is very warm near the heated ceilings of the reading room (upper frame) and lending area (middle and lower frames). Air temperature in the lecture hall cools significantly during the one hour of simulation time. The temperature throughout the remainder of the building remains relatively constant over time. Air velocities throughout the building are low as shown in Fig. 6(b). The highest velocities occur near the inlet at the front door (middle frame) and near the exit at the rear door (lower frame). For this set of conditions, the low velocities and stratified air temperatures imply that heat transfers primarily through diffusion. The fluctuating high

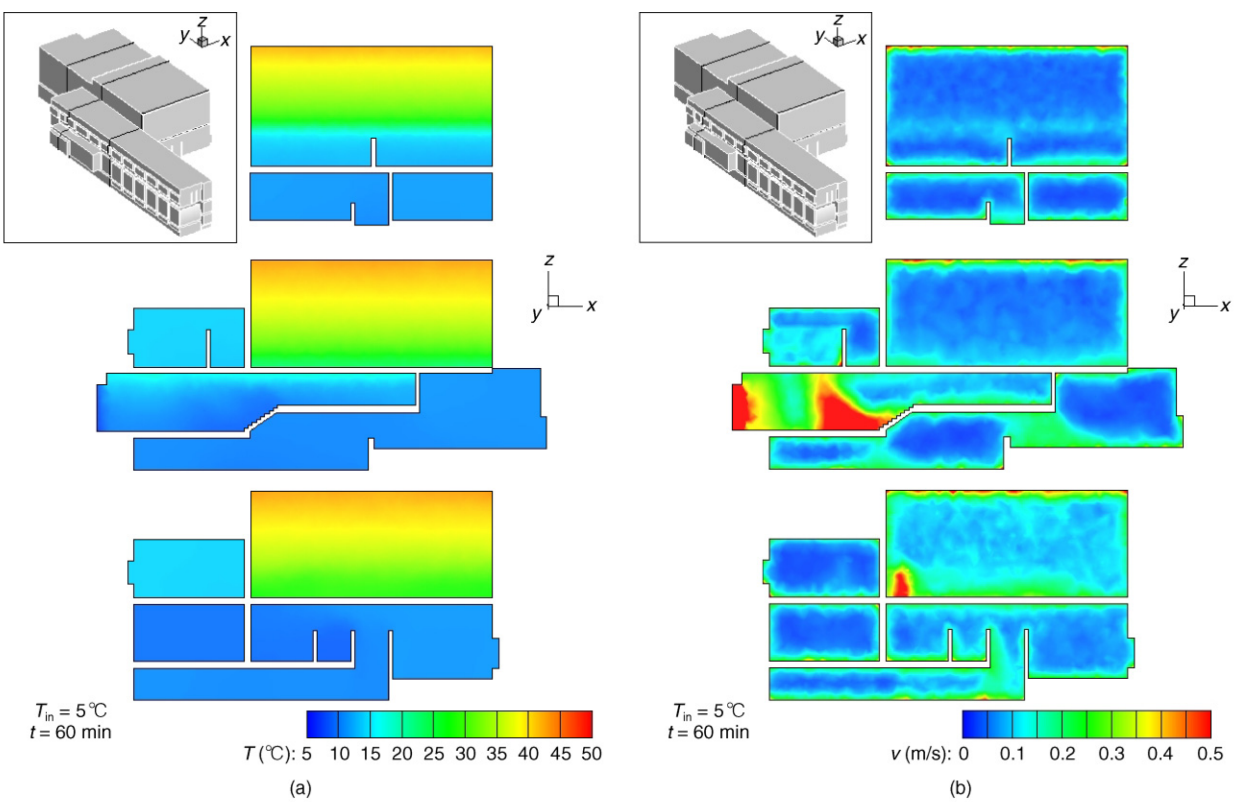

Fig. 6 Contours of (a) temperature and (b) velocity at 60 min for the reference heating case at selected *x*-*z* planes. Upper frame shows the reading room, middle frame shows the lending and entrance areas, and lower frame shows the lending area and lecture hall

and low velocities near the heated ceiling in the reading room shows evidence of a buoyancy-driven flow.

Of importance to the restoration of the library is being able to ventilate the building. Although natural convection is not dominant, there is sufficient airflow through the building because the front and rear doors are propped open, and this can be characterized as *natural ventilation*. Figure 7 shows *y*-*z* planes with views of the reading room and lending area (upper frame); the reading room, lending area and the rear door (middle frame); and the entrance area, lecture hall and office space (lower frame). Overall, for this particular case, the air moves with an average velocity of 0.1 m/s throughout the building and this information can be very useful when evaluating the demand on the mechanical ventilation system.

To fully appreciate the flow field changes over time, Fig. 8(a, b) shows the progression of average temperature and velocity, respectively, for selected locations in the library. The data is spatially averaged over planes that are at 1 m and 1.8 m above the floor in the reading room and lending area; these heights correspond to approximate locations of a person's head while seated and standing, respectively. ASHRAE Standard 55-2004 (ASHRAE 2004) states as a general guideline that temperatures within a naturally ventilated building can reach 28℃ with an air velocity up to 0.8 m/s. The velocities quickly reach steady state around 10 min and do not rise above the 0.8 m/s ASHRAE threshold. The temperature within the reading room remains relatively

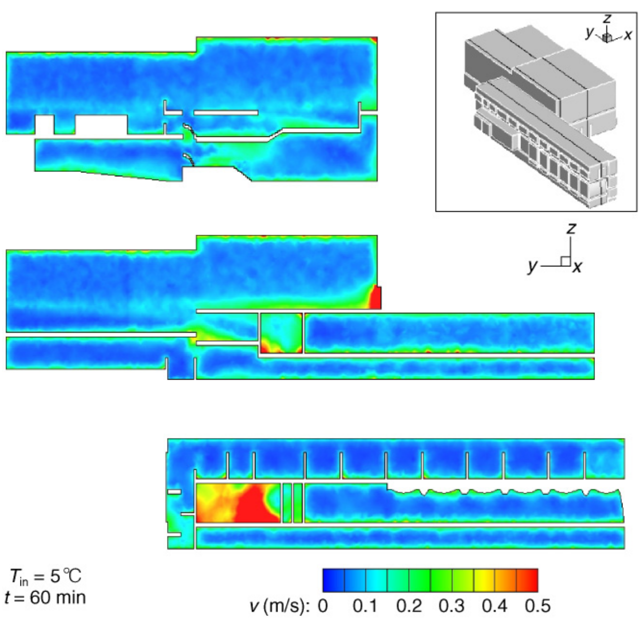

Fig. 7 Contours of velocity at 60 min for the reference heating case at selected *y*-*z* planes. Upper frame shows the reading room and lending area, middle frame shows the reading room, lending area and the rear door, and lower frame shows the entrance area, lecture hall and office space

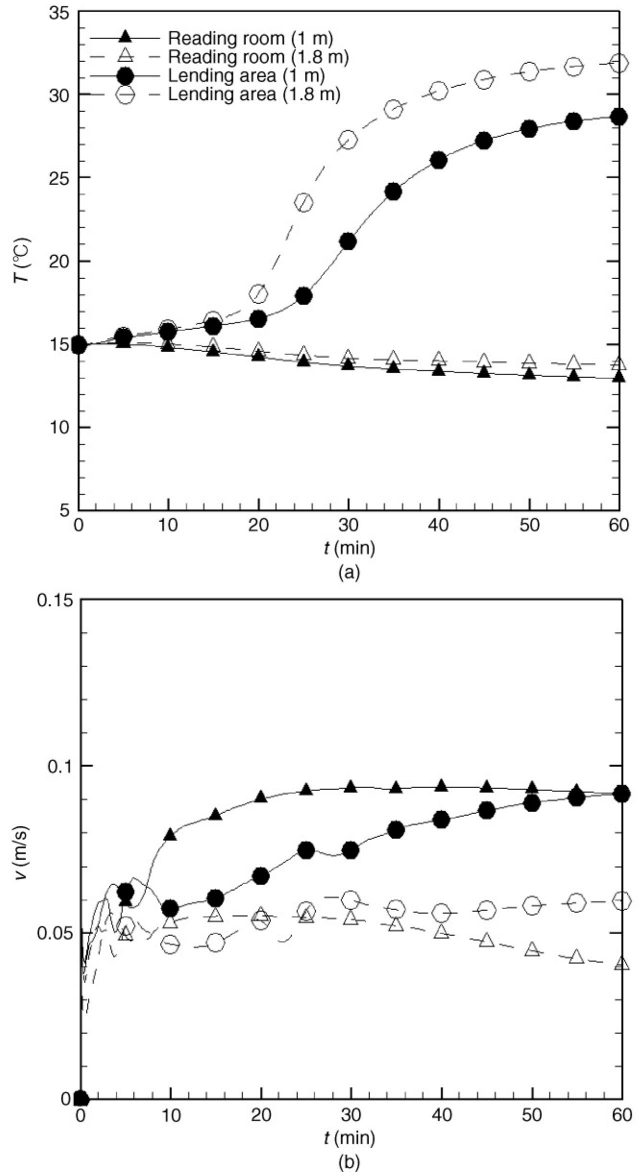

Fig. 8 Average (a) temperature and (b) velocity versus time at selected locations for the reference heating case (with T_{atm} = 5℃)

constant with a one degree decrease. However, after approximately 20 min, the temperature in the lending area sharply increases and reaches a steady state after one hour but exceeds the ASHRAE recommendations by 4℃. It should be noted again that the reading room and lending area are on split levels of the library; thus the distances between the floor and ceiling in the reading room and lending area are 8.6 m and 7.7 m, respectively. Therefore, the closer proximity of the ceiling accounts for the more significant temperature variations in the lending area.

4.2.2 *Effects of atmospheric changes*

To study the effects that atmospheric changes have on the heating of the library, the ambient air entering the central door is reduced to $T_{atm} = -5$℃ and all other parameters remain the same as the reference heating case. Figure 9(a, b) shows the time progression of the air temperature and velocity, respectively. The average temperature in the lending area (Fig. 9(a)) is about 4℃ cooler 1 m from the floor and 2℃ cooler 1.8 m from the floor after 60 min, when compared to the reference heating case in Fig. 8(a). Temperatures within the reading room reach 10℃, which is 4℃ cooler than the reference case. The velocities in the lending room are higher when $T_{atm} = -5$℃ but the rest of the velocity trends are similar with the reference heating case. Thus, there is evidence that colder outdoor temperatures result in larger temperature gradients throughout the library, which increase airflow as convection currents develop. Although additional conditions could have been considered, such as changing the wind velocity outdoors, these current results demonstrate the impact of the interior spatial composition and how it changes the air velocity *within* the building.

4.2.3 *Effects of main entrance configuration*

An additional simulation was performed to study the effects of changing the orientation of the open entrance door. For this simulation, the left door (see Fig. 3(a)) is opened and all other parameters remain the same as the reference heating case. Figure 10(a, b) shows the progression in time for the average temperatures and velocities in the lending area and reading room with the left door ajar. The trends for temperature and velocity are very similar to the curves

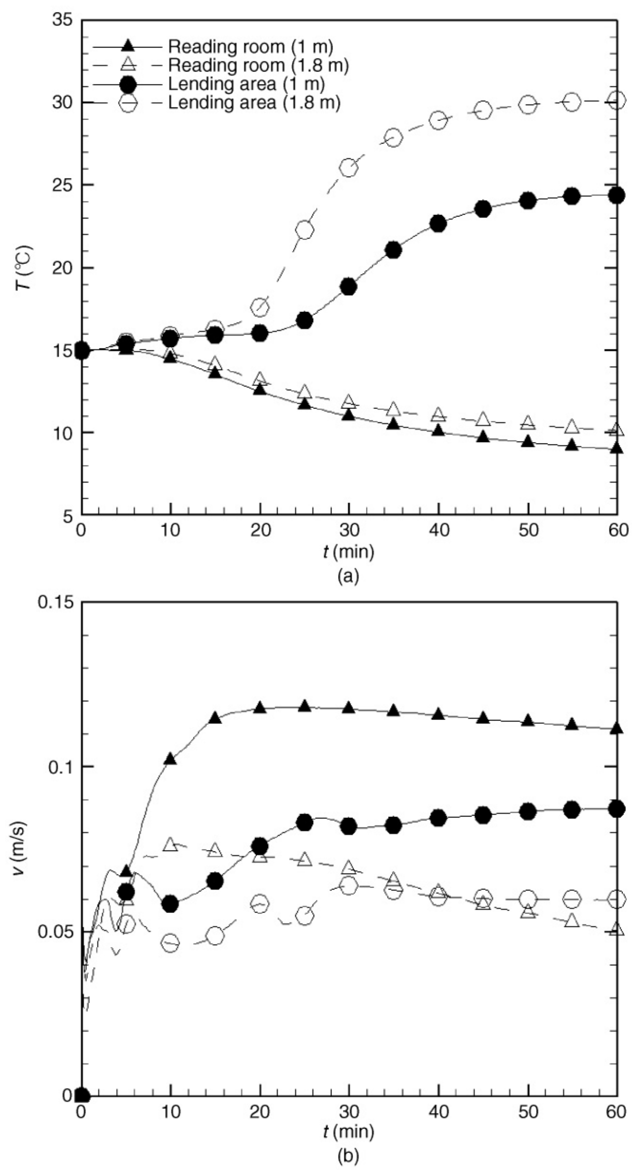

Fig. 9 Average (a) temperature and (b) velocity versus time at selected locations for the heating case with $T_{atm} = -5$℃

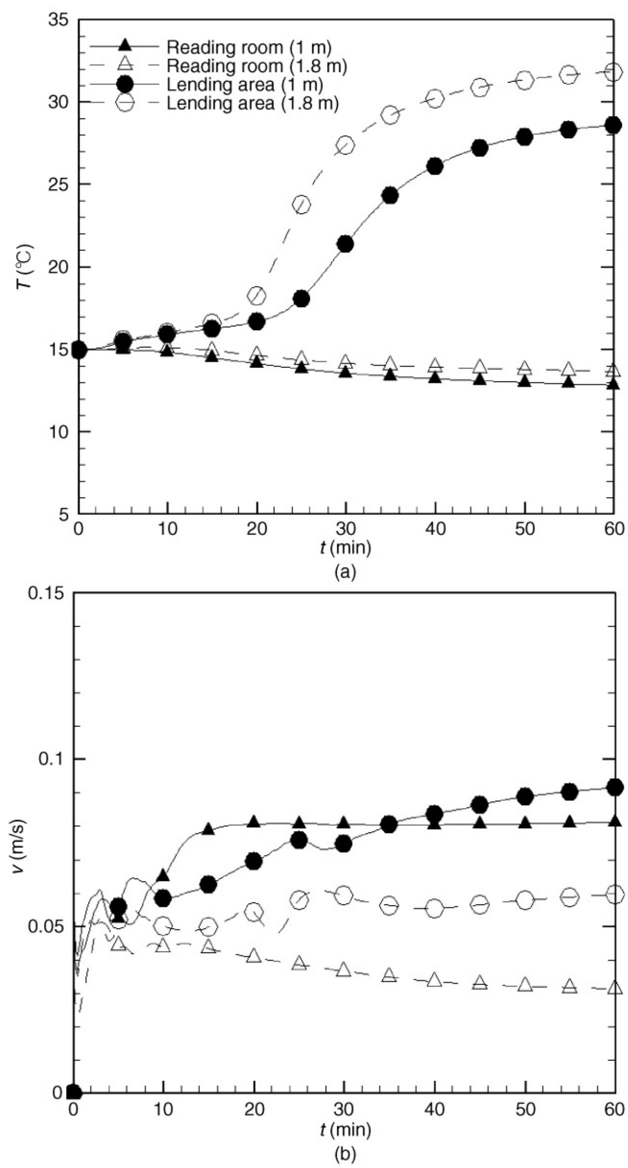

Fig. 10 Average (a) temperature and (b) velocity versus time at selected locations for the heating case ($T_{atm} = -5$℃) with the left door open

shown in Fig. 8. However, it was also observed from these simulations that cooler air is present in the entrance area and stairwell when the left door is ajar as compared to the reference case. Beyond this difference, there was no significant effect by changing which door was opened for ventilation. Thus, this case study demonstrates that the overall thermal comfort of the library is not negatively affected by propping open a different door; only changes in the outdoor temperature affect both thermal comfort and the amount of air exchange within the building. Furthermore, the large open spaces of the library are conducive for exploiting natural ventilation by merely propping open two doors at opposite end of the library, while maintaining thermal comfort during the winter months.

4.3 Passive cooling study

During the summer months, the library is cooled using natural airflow through the building, whereby air enters through the front door of the library and exits through the rear door. A total of three simulations were performed for the passive cooling scenarios to replicate a morning during the month of June, based on weather conditions averaged over a 5-year period (NCDC 2011). All front doors were modeled as completely open with wind entering at a velocity of 2.2 m/s normal to the opening at a temperature of 20℃. The back door was modeled as being completely open to allow for cross ventilation within the building. The initial temperature T_o of the building for all cases was set to 27℃ with no air movement to model conditions when the library is first opened. As with the "Radiant heating study", the building was modeled unoccupied to understand how well the space itself supports natural ventilation in order to bring the building into a condition of thermal comfort. A summary of boundary conditions for the passive cooling cases is given in Table 3. For all cases, $Ra \approx 10^{12}$, indicating that the airflow is turbulent. The time step used for the transient simulations was 0.1 s; most simulations required around 20 – 30 iterations per time step. The convergence criteria were satisfied when residuals dropped at least three orders of magnitude and the change among all residuals was less than 1%. The cooling cases were simulated up to a time of 20 min and required approximately 110 CPU hours.

Table 3 Summary of the Viipuri Library cooling cases

	Reference case (§4.3.1)	Doors and windows (§4.3.2)	Doors, windows, children's library door (§4.3.2)
Inlets	Main entrance	Main entrance and office windows	Main entrance and office windows
Outlets	Rear door	Rear door	Rear door and children's library door
v_{atm} (m/s)	2.2	2.2	2.2
T_{atm} (℃)	20	20	20
T_o (℃)	27	27	27

4.3.1 *Reference cooling case*

The reference cooling simulation is shown in Fig. 11(a, b) for temperature and velocity contours at 20 min at planes 1 m and 1.8 m above the floor in the lecture hall, the reading room and the lending area. The reading room and lending area (upper and middle frames of Fig. 11(a)) cool very quickly and reach a temperature of 21℃. The middle and lower frames show that the office space does not cool as readily, and by 20 min the air temperature is near 26℃, whereas the lecture hall is close to 22℃. Interestingly, the middle frame of Fig. 11(b) shows high air velocities near the front doors and the lower frame shows even higher velocities near the rear door. All three frames show that elsewhere in the building, the air velocities remain low.

Figure 12(a) shows that the average temperatures in the lending area and reading room quickly drop by almost 7℃ during the first 5 min and reach a steady state after about 15 min. The lecture hall does not cool as quickly, but after 20 min the average temperature in the lecture hall is below 21℃. Figure 12(b) shows that the average velocities reach steady state by 5 min in all three rooms but are above the recommended value of 0.2 m/s; however, they remain under the acceptable range of 0.8 m/s. The ambient conditions used to model the reference case demonstrate that once the library is opened for business, the warm air within the library cools rapidly due to the natural ventilation. The key is that the doors must be completely open to provide the maximum amount of air exchange.

4.3.2 *Effect of door and window configuration*

An additional simulation was performed to examine the effect on airflow and temperatures in the building when every other window in the row of offices on the second floor is opened (see Fig. 13(a)). As will be shown, opening the windows on the second floor aids in cooling the air in the offices as well as in the lecture hall on the first floor; however, the velocities throughout the library increase considerably, which is expected because a larger volume of air is entering the building.

Figure 13(a) shows that the temperatures throughout the building decrease very quickly to just above 20℃ during the first 5 min, especially compared to temperatures in the lecture hall for the reference cooling simulation (Fig. 12(a)). It was also observed that the temperature in the basement of the library was much lower when the office windows were open. The velocities (Fig. 13(b)) are significantly higher in all three rooms, reaching a maximum of 2 m/s in the reading room, when compared with the reference case (Fig. 12(b)). Unfortunately, the velocities exceed the acceptable range recommended by ASHRAE and motivate the next simulation for passive cooling.

The final case modeled air entering the front door and the windows in the office and exiting not only the rear door, but also the door in the children's library. The objective of opening the door in the children's library was to reduce the air velocity in certain areas of the library (i.e., near the rear

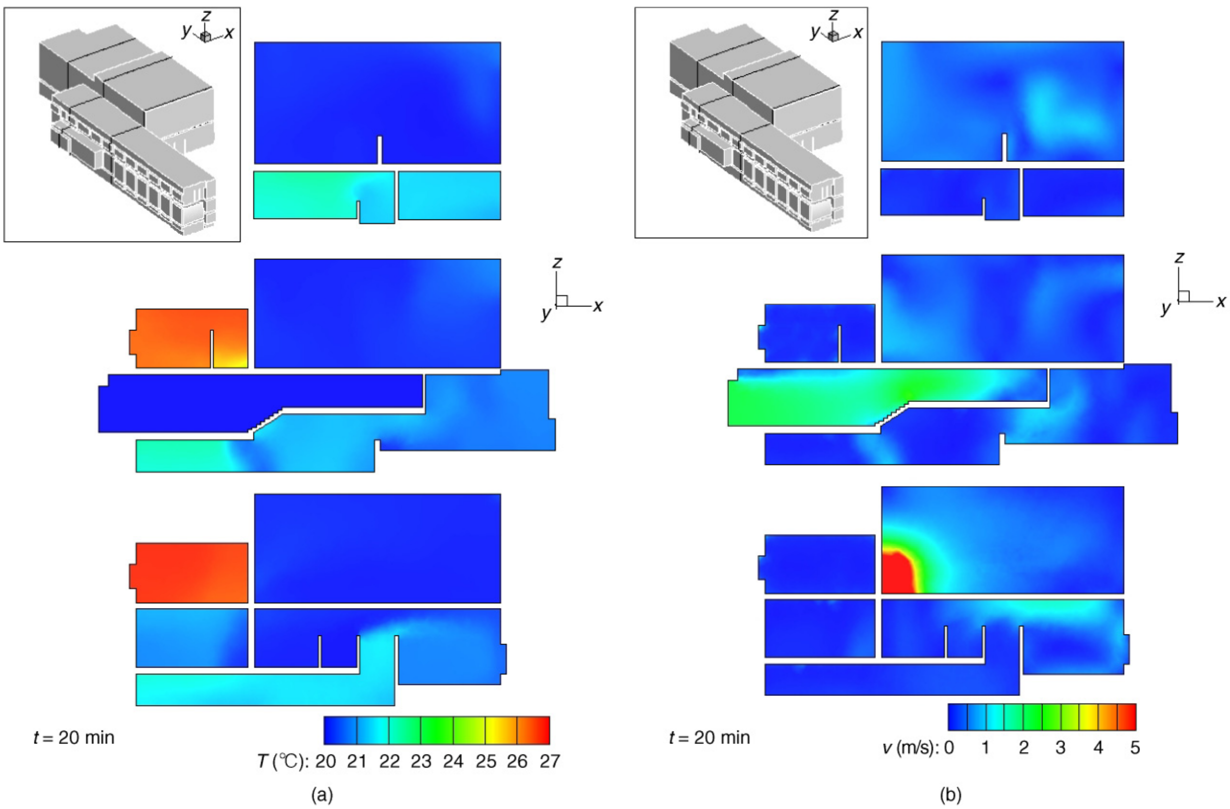

Fig. 11 Contours of (a) temperature and (b) velocity at 20 min for the reference cooling case at select *x-z* planes. Upper frame shows the reading room, middle frame shows the lending and entrance areas, and lower frame shows the lending area and lecture hall

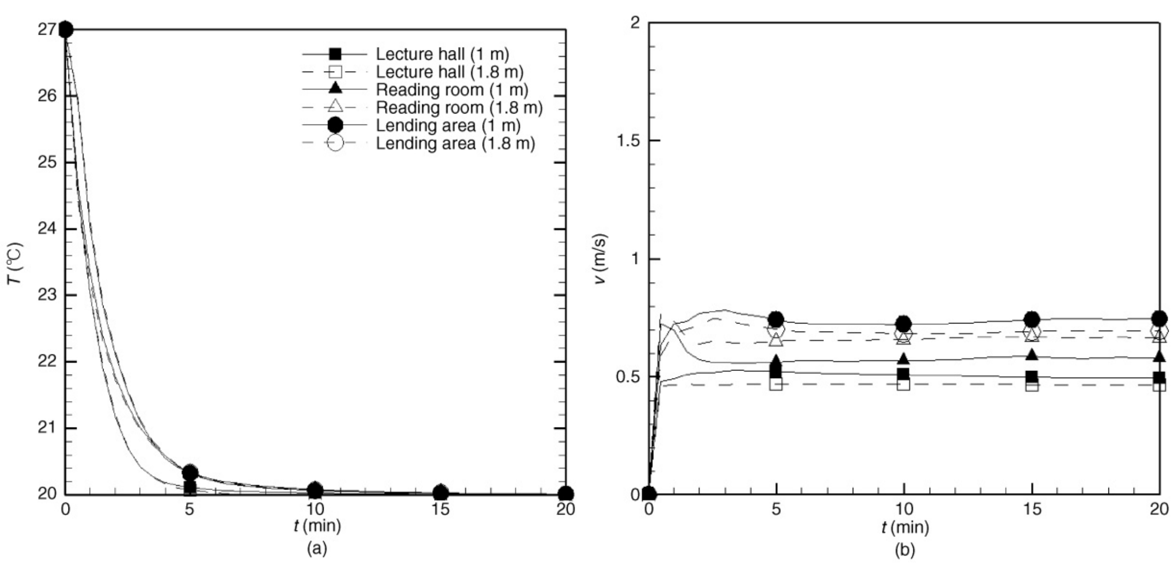

Fig. 12 Average (a) temperature and (b) velocity versus time at selected locations for the reference cooling case (front and rear doors open)

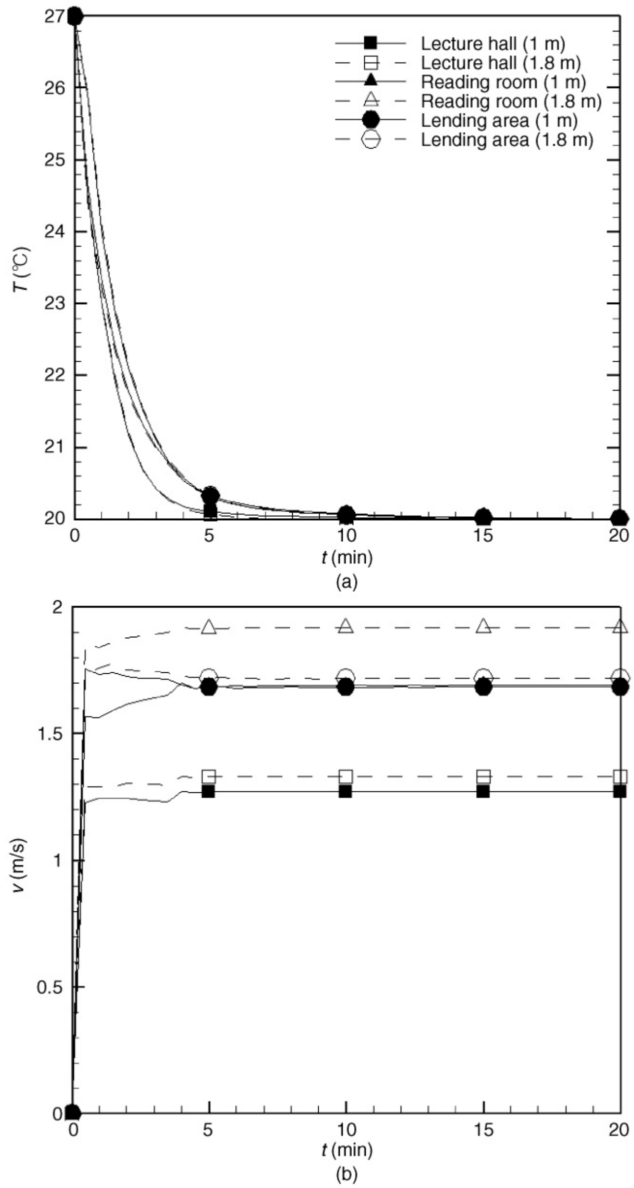

Fig. 13 Average (a) temperature and (b) velocity versus time at selected locations for the case with front door, rear door and office windows open

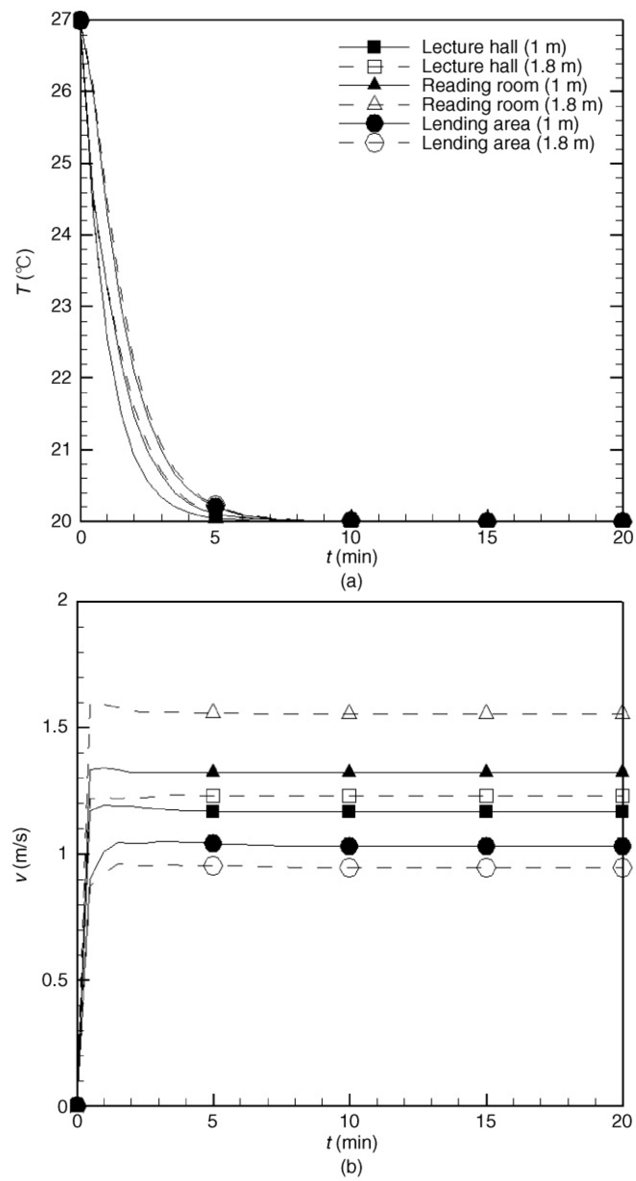

Fig. 14 Average (a) temperature and (b) velocity versus time at selected locations for the case with front, rear and children's library doors and office windows open

door, between the two levels of the stacks, etc.). Figure 14(a, b) shows the air temperature and velocity when the children's library door is open. Similar to the second passive cooling case with the front and rear doors and the office windows open, the average temperatures throughout the building decrease quickly. Of particular interest is the air velocity (Fig. 14(b)), which has decreased from 2 m/s to 1.5 m/s throughout the entire building; however, the velocity is still higher than the standard set by ASHRAE. It is worth noting that allowing for an additional exit area, such as opening the children's library door, decreases the air velocity throughout the building, especially near the rear door in the lending area.

These two case studies demonstrate that the air movement within the library can be excessive unless there is a balance between the number of doors and windows that are open.

5 Concluding remarks

Computational fluid dynamics (CFD) was used to model, simulate and predict natural ventilation by means of heating and passive cooling in the Viipuri Library, a historical building of the Modern era that is currently being restored. The novelty of this research is using CFD to simulate whole buildings. Much of the previous research using CFD to study natural ventilation in buildings modeled simple buildings, often a single room with openings to the atmosphere and no interior obstructions. The CFD simulations in this work used the commercial package FLUENT to solve the three-dimensional Navier-Stokes equations.

The heating study modeled the library's hot water pipes in the ceiling as a constant surface temperature in the lending area, reading room, and near the main entrance. The front and rear doors were held ajar to allow airflow through the building and assist with circulation of the warm air near the ceiling. Three scenarios were modeled and simulated to examine temperatures and velocities within the building. It was found that colder outdoor temperatures resulted in larger temperature gradients throughout the library, thus increasing the airflow. Furthermore, the large open spaces of the library are conducive for exploiting natural ventilation by merely propping open two doors at opposite end of the library, while maintaining thermal comfort during the winter months.

The passive cooling study modeled the library during the summer months using natural ventilation, whereby the front and rear doors of the library were completely propped open to create crossflow within the building. The reference case modeled the building with just the front and rear doors open and predictions showed the building cooled nonuniformly, with the office space remaining at elevated temperatures. When the office windows were opened, the entire building cooled more uniformly, but excessively high velocities were found throughout the building. It was decided that the high velocities were caused by the presence of only one exit from the building, forcing the air entering the front door and office windows to exit the rear door. The final simulation with the children's library door open demonstrated that the library cooled sufficiently and had slightly lower velocities within the building. Thus, natural ventilation during the summer can be carefully controlled with a proper balance between the number of windows and doors open on opposite sides of the library.

For the ongoing restoration effort of the Viipuri Library, implementing the knowledge gained through this study could lead to a more efficient mechanical HVAC system design. As previously mentioned, the existing ventilation ducts have not functioned in years, and are still considered the only means to bring controlled conditioned air into the reading room, which has no operable windows in its core space. The historic preservation requirements prevent the addition of new ducts in the reading room yet the existing ducts are not sufficient by current standards to supply the necessary air change rates. A hybrid system based on the original ventilation ducts and a well understood natural ventilation strategy using CFD could jointly meet current needs while preserving the historic system. Further research based on this study will enable the extraction of design guidelines for natural ventilation in large open spaces with split level spatial compositions. Thus, this work will not only provide recommendations for historic building restorations where natural ventilation might be in operation, but help guide or re-introduce natural ventilation into contemporary library designs, which are commonly fully conditioned buildings.

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