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Field investigations of stack ventilation in a residential building with multiple chimneys and tilted window in cold climate

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ABSTRACT

Ventilation stacks are becoming increasingly common in the design of naturally ventilated buildings. They offer a method for achieving a fixed flow pattern irrespective of internal and external conditions. In this paper, the field measurements results are presented on the stack ventilation effect in a configuration with multi-chimneys which interact with tilted pivot windows. A residential two-family detached house was chosen to perform the measurement campaign. The house was located in a cold climate region in northern Poland. The measurements were performed in June during the time period of transient climate conditions between spring and summer. Local climate conditions, indoor climate conditions and air velocities in vent inlets and outlets were measured. In order to interpret measurement results, a modified model of a tilted pivot window with an axis at the bottom was proposed, based on a model used in single-sided ventilation investigations. The measured results confirmed the usefulness of the proposed approach. The loss coefficient (discharge coefficient) of 0.345 was lower than the loss coefficient of 0.60, usually assumed for small rectangular openings during natural ventilation. In the absence of wind when the stack effect acted only, the air changes per hour slightly exceeded the standard minimum value. The tilted window leeward wind significantly reduced the stack effect and ACH.

1. Introduction

Since the ventilation makes up for the about half of the energy consumption in well-insulated buildings, it is a very attractive potential for the massive gross energy saving. A simple reduction of ventilation rates however deteriorates the indoor air quality and therefore causes unwanted effects such as an increase of respiratory illnesses and a productivity loss [20]. In hot climate conditions with a high humidity, the properly designed natural ventilation may result in a significant reduction of the discomfort from a moist human skin due to an increase of the air velocity above the human body [1]. The growing interest in a reducing building energy demand for heating and cooling is directed to the natural ventilation which is cheap during the construction and maintenance. The natural ventilation is one of passive means for energy savings which effectiveness and performance depend on many factors, such as: size and location of openings [2,3], location of inlet gaps, ambient climate conditions, etc. The natural ventilation is able to create the thermal comfort and healthy indoor conditions while poorly designed naturally ventilated buildings may be uncomfortable for both living and working.

There are several concepts of natural ventilation. Depending upon techniques and strategies, three general concepts may be distinguished [4]: single-sided ventilation, wind-pressure driven cross-ventilation and buoyancy pressure-driven stack ventilation. Ventilation stacks are becoming increasingly common in the design of naturally ventilated buildings. They offer a method for achieving a fixed flow pattern irrespective of both internal and external conditions. The stack ventilation is driven by a temperature difference between the outdoor and indoor air density. It is mainly affected by a wind direction and velocity.

There exist different concepts on how to locate air inlets and air outlets and how to create a stack effect. Many researchers propose to enter the fresh air via large openings like doors and windows, while a stack effect is created in large ducts designed by a particular indoor space arrangement. One of the most popular method to create the stack effect are large and high open spaces (like atria). Acred and Hunt [5] studied natural ventilation in a multi-storey building with an atrium. They developed a simplified mathematical model for a preliminary design strategy and proposed an atrium enhancement parameter which quantified the performance of the ventilation system and the atrium effectiveness to promote air flow. They applied successfully the method in several buoyancy-driven

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ventilation buildings with a simple geometry. More advanced simulations for atrium geometries were performed by Rundle et al. [6]. They used the commercial Computational Fluid Dynamics (CFD) code to study physical phenomena in atria including turbulent natural convection, radiative heat transfer and conjugate heat transfer. They concluded that the CFD model was capable to describe the stack effect and to improve the house design. The complex air flow in atria was governed by the unique nature of physical phenomena which were not usually taken into account in traditional building energy simulations. Rundle et al. [6] provided a systematic validation of the commercial CFD code against experimental measurements of underlying physical phenomena. The authors concluded that CFD might be used successfully to simulate heat transfer and fluid flow in atria geometries. They provided some recommendations with respect to the turbulence and radiation heat transfer modeling.

In hot and moderate climates, the natural passive ventilation is often designed to cool indoor zones of buildings. The popular technique is to pre-cool the indoor space by the natural ventilation during nights. The results by Becker and Paciuk [7] and Givoni [1] showed that the night pre-cooling was an extremely efficient cooling technique for buildings with high internal heat loads since it reduced the internal mass temperature below the air temperature (consequently it decreased the peak power requirements). In cold climate zones, the basic aim of the natural ventilation design is slightly different. The ventilation system should primary maintain the air quality during a heating time period rather than to cool indoor zones during summer. Hence, the most common natural ventilation configuration in cold climate regions is a stack ventilation. The stack effect may be created in different ways, however, a common rule is to design one vertical duct or some ducts. The duct outlet is in a contact with the ambient air. The air inlets can be designed in multi-compartment buildings as a vertical duct (atrium) to develop the stack effect. It is relatively easy to control mechanical ventilation systems to maintain the best air exchange rate [8–11] while for natural ventilation, in particular for the stack ventilation in a configuration with multi-chimneys, it is more difficult to control the airflow characteristics and its rate. The performance of the stack ventilation with multi-chimneys depends strongly on the configuration and climate conditions. The well designed ventilation should reduce an influence of wind gusts during a winter in order to decrease the energy demand while windows should be operable to enable the night cooling during summers and to give an additional control during winters. In order to reduce the energy demand and maintain the thermal comfort, the basic air inlets are located in the building envelope and have a very small active area (the chimneys outlet ducts active area are also small). There are very few research studies concerning natural ventilation in a configuration with multiple stacks in cold climate conditions. Wang et al. [12] investigated experimentally natural ventilation through multiple stacks on a scale model of one sealed room. They observed that for all opening configurations tested, a flow reversal occurred for at least one wind direction and the reversal percentage measured in the model was dependent upon the building Reynolds number. Gładyszewska-Fiedoruk and Gajewski [13] experimentally investigated the wind impact on the stack ventilation with multi-chimneys in kindergartens. Their investigations were limited to the air change rate (ACH) and CO_2-concentration. They concluded that stack ventilation was capable of ensuring the appropriate IAQ inside buildings during winter and the stream of the removed air used might be up nearly 3.5 times greater during a windy weather than under windless conditions. In general, the stack ventilation in a configuration with multi-chimneys is very difficult for controlling the air quality and thermal conditions. Thus, residents have to use operable windows. The common practice is to slightly tilt a window or windows. In many cases, the operable pivot windows with an axis at the bottom are sufficient. There research results are lacking on how a tilted window interacts with multi-room indoor zones with chimney air outlets and how it influences a stack effect which is a dominant factor when stabilizing indoor conditions.

In this paper, the field measurements results are presented on the stack ventilation effect in a residential building with multi-chimneys under cold climate conditions, which interact with a tilted pivot window. The window leeward and windward wind directions and the ventilation effectiveness and performance in unsteady conditions were analyzed in detail. The field measurements were performed in a separate test apartment on the second floor of a two-family detached house. The measurement campaign started on 11th of June 2013 at 12:00 O' clock and ended on 17th of June 2013 at 12:00 O' clock during transient climate conditions (the stack effect was investigated during the time-period of steady climate conditions in the wind absence from 1:30 O' clock on 13th of June 2013 to 4:30 O' clock on 13th of June 2013).

The major contribution of the paper is the experimental determination of the stack effect in residential houses with multi-chimneys configuration and a tilted window (equipped with the natural stack ventilation) on the air exchange rate. Since the stack ventilation in a configuration with multi-chimneys has been used for decades in residential buildings located in cold climate regions of northern, eastern and central Europe, the problem is certainly important for these regions. Recently, natural ventilation has become also a meaningful alternative to mechanical systems in low-energy buildings in different climate zones. Despite a short measurement period, our research findings may be already helpful for practitioners in order to improve a stack ventilation design with the aim to reduce energy consumption at the beginning of the design process.

2. Test house

The natural stack ventilation in a configuration with multi-chimneys is very specific. This configuration is strictly regulated by national regulations and standards [14]. Small inlet gaps are located in windows frames or above windows openings and equipped with controllable vent grills. The active flow area of inlets should meet requirements to enable the total flow rate of $180.0\,\mathrm{m}^3/\mathrm{h}$ by $\Delta p = 10\,\mathrm{Pa}$ (ambient – indoor). The inlet gaps are located in each room being in a contact with the ambient air. The air outlets to the chimney ducts of $14 \times 14\,\mathrm{cm}^2$ (min. $0.016\,\mathrm{m}^2$) are located in bathrooms, kitchens and technical (utility) rooms without window openings. The air inlets into the chimneys ducts are equipped with controllable vent grills. They are located maximum 0.15 m below the room ceiling. Thus, the stack effect is created only in the chimneys ducts. The chimneys outlets are above the building aerodynamic shadow. The above ventilation configuration intends to reduce the wind gust impact on the air exchange rate during the wintertime, and consequently on the building energy demand. Thus, the stack effect has to be large enough to move the waste air out through chimneys ducts during no-wind time periods and to stabilize airflow profiles during wind-time periods. In contrast to wintertime functions, the air exchange control is based on operable windows in winters. Hence, during the summer time, the ventilation system operates as a cross-ventilation rather than a stack ventilation. The vent air inlets and outlets are located at almost the same height from the floor and close to the ceiling. Under cold climate conditions of northern Poland, the ventilation works in a winter regime from October to May. A typical summer period happens in July and August. All other time periods may be called the transient climate conditions (TCCs). TCCs are characterized by a day temperature difference between