CFD investigation of natural ventilation in a family house in Hungary

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Abstract. Buildings are responsible for around 40% of greenhouse emissions globally. The residential building sector is responsible for 24% of energy use. In Hungary, about 800,000 ‘Cube houses’ which date back to the socialist era are still standing. These houses suffer shortages from the energy point of view. This paper presents a new refurbishment approach that attempts to achieve passive cooling with aerodynamic design by integrating the “Venturi disc” which stimulates natural ventilation and night cooling. The work was achieved by using Computational Fluid Dynamics (CFD) simulations using ANSYS Fluent software tool. The implemented building provides lower energy demand and considerably higher comfort in comparison with the typical ‘Cube house’. The building is not only a case study, rather a sustainable model for all the ‘Cube houses’ renewal and further family housing renovations or constructions to reach a higher standard. This paper is a step in an ongoing research project.

1. Introduction
Buildings are responsible for nearly 40% of final energy consumption in the EU [1, 2]. Building energy usage is caused by many building services. Heating, ventilation, and air conditioning (HVAC) systems are the largest energy consumers comparing to other building services and ventilation is a crucial factor [3]. Natural ventilation has been promoted as an effective strategy to limit energy consumption in buildings by providing high indoor air quality (IAQ) [4]. Natural ventilation can be helpful to fulfill the cooling need and limit the dependence on mechanical air conditioning systems. Successful natural ventilation also helps to meet the required indoor thermal comfort which reduces the use of HVAC [5]. The building sector can play an important role to improve energy efficiency. This role was highlighted in the European Commission’s Communication on energy efficiency in the light of achieving energy security and the 2030 framework for climate and energy policy [1]. By 2030, the largest portion of carbon reduction in the building sector will come from retrofitting existing buildings and improving the energy efficiency of their equipment and appliances [6]. A European Commission report [7] highlights the social, environmental, and economic benefits of renovating existing buildings, especially that only 11% of the EU existing buildings experienced some level of renovation and only 1% were renovated with considering the energy consumption [7]. This percentage needs to at least be doubled to reach the EU’s energy efficiency and climate objectives as The European Green Deal stated [8]. According to the
2020 European Commission Country Report, the energy consumption of the residential sector in Hungary surpasses the EU average by 12%. More efforts are required for improving buildings’ energy and efficiency as a part of a National Energy and Climate Plan. However, the report points to the big potential for improvement by applying stricter energy efficiency standards for new buildings and refurbishing the existing housing stock and public buildings [9]. When conducting a study on residential buildings in Switzerland and their refurbishment methods in light of the energy transition goals, Flourentzou [10] concluded that deep energy refurbishment is required to reduce the performance gap.

The so-called ‘Cube houses’ are typical single-story small detached houses that have been built in Central and Eastern Europe after the second world war in an attempt to replace older traditional buildings [11]. They have been built in Hungary since the 1960s. It is a family house consisting of two bedrooms and is usually equipped with a gas boiler for heating and an electric boiler for Domestic Hot Water (DHW). More than 800,000 units were constructed, hence this type can be considered as a typical family house in Hungary [12].

Venturi disc is a disc-shaped roof installed at a certain height above the building. It causes the so-called Venturi effect which creates a negative pressure zone in the narrowest part under the disc. This negative pressure causes a suction effect that can drag the air from inside the building and causes natural ventilation [12, 13]. It can be argued that the idea of utilizing the Venturi disc started with the windcatcher which is one of the oldest passive cooling systems. Many studies have dealt with the natural ventilation induced by windcatchers bringing IAQ and thermal comfort. The studies adopted two main approaches; the experimental approach which contains full-scale measurements or laboratory scale measurements, and the theoretical approach which contains Computational fluid dynamics (CFD) [14]. Some studies dealt in particular with the Venturi effect in buildings [12, 15-19].

Hooff et al. [15] evaluated different design configurations of a Venturi-shaped roof by wind tunnel measurements and CFD simulations. The study showed the roof’s potential of driving natural ventilation into the building’s comfort zones.

Kistelegdi et al. [16] conducted a wind tunnel test of an industrial building in the middle European climate conditions. The building is designed with 3 ventilation towers each of which is equipped with a Venturi-shaped structure. The Venturi structure caused high efficiency in passive ventilation. Katona et al. [17] carried out a CFD modelling of the building where the role of the Venturi structure in creating reliable updraft ventilation was validated.

Farzan et al. [18] tested a specific Venturi-shaped roof where the Venturi effect could be detected and analysed. The results showed the potential the Venturi-shaped roof has in bringing considerable ventilation and ACH to the building in hot and humid climates.

Haw et al. [19] investigated the natural ventilation caused by a Venturi-shaped roof in hot and humid climates. Even though the outdoor wind velocity was below 0.5 m/s, the results showed a great potential of the applied geometry in generating sufficient airflow and 57 Air Change (ACH).

Boroojerdian et al. [20] compared the effectiveness of 3 different formations of the Venturi disc in inducing ventilation using a wind-tunnel test. The tested formations were the shallow ellipse, the ellipse, and the hemisphere. It was found that the shallow ellipse had the best performance.

CFD simulations have been largely used when designing and analysing buildings due to their ability to provide a comprehensive overview of the building’s thermal comfort, airflow velocity, air temperature, and many other indicators for indoors and outdoors environments [3]. In literature and the research community, CFD was the most prevalent tool to predict ventilation performance because of its reliability and good agreement with analytical models and experiments. In addition to its ability to be used with other simulation tools to reduce the needed computing power [21].

The case presented in this research was a participation in the Solar Decathlon Europe 2019 (SDE19) competition which took place in Szentendre, Hungary. The authors have demonstrated in previous research that the new design of the house brings 52.3% of saving in energy consumption when compared to the typical ‘Cube house’. The dynamic energy simulations showed that energy demand, daylight provision, and indoor comfort and air quality were significantly improved [22].
2. Methodology
CFD is a numerical application method that is widely used in many aspects of building design. It is a highly accurate tool that employs equations of fluid mechanics [23]. The methodology of the paper consists of two main steps; the first step is the grid independency analysis which validates the chosen CFD mesh, and the second step is a detailed CFD analysis which evaluates natural ventilation within the investigated scenarios.

3. Case Study

3.1. Building description
The case study is a free-standing one-floor family house of a timber structure (as shown in Figure 1). The house is located in Szentendre, Hungary, and has a floor area of 65 m². It was built as a refurbishment proposal of the traditional Hungarian ‘cube houses’. The timber as a structure was most suitable for the competition requirements even though this type of house is not typically built of timber. Nevertheless, this does not make a significant difference regarding the airflow investigation. The house is equipped with a ‘Venturi’ disc on the top which is connected to a small atrium as a ventilation chimney. It is designed to create a suction effect and stimulate natural ventilation through the house. The house is elevated above the ground by 21 cm and is equipped with four floor openings through which fresh air can enter. Figure 1 shows the proposed method as it is tested in the numerical CFD simulation. The ‘Venturi’ disc measures 323 cm in diameter and 15 cm in height leaving a 48 cm-height air gap from the shaft whose horizontal section measures 180*180 cm.

3.2. CFD model

3.2.1. Mesh generation. The size of the computational domain (Figure 2) was created according to the recommended practice guidelines. The height is 7h and the horizontal dimensions are 10*10 h; where h is the building’s height and h = 7 m. The meshing was done with an unstructured hybrid mesh which used the multizone method and combined hexagonal, tetrahedral, prism, and wedge cells. Figure 3 shows a part of the mesh arrangement in a vertical section.
3.2.2. **Boundary conditions.** The simulation was handled with ANSYS R.17.2 software. The 3D geometry was created identical to the documentation plans and to the constructed building. Wind direction was set to one direction (from the north) after applying the local wind profile of the suburban area where the location is. The inlet of the computational domain is defined as velocity inlet, and the outlet as pressure outlet, and the top boundary as symmetry boundary condition. The weather data and wind profile were acquired from the Meteonorm database [24].

One wind direction was tested since the prevailing wind direction in Hungary is from the north [25]. Airflow and temperature were simulated after setting the date to 21st of September at 1 p.m. since the transitional seasons are the most suitable time of the year to utilize natural ventilation. Heat sources were set in the kitchen and the living space representing kitchen appliances, a TV, a PC, and four people; two seated, one standing, and one cooking. Table 1 shows heat emissions from the set heat sources.

**Table 1.** Implemented heat sources in the simulation model.

| Location     | Heat sources     | (W)  |
|--------------|------------------|------|
| Sitting area | PC               | 40   |
|              | TV               | 40   |
|              | Seated person    | 108  |
|              | Seated person    | 108  |
|              | Standing person  | 126  |
| Kitchen      | Cooking person   | 207  |
|              | Coffee machine   | 250  |
|              | Electric oven    | 800  |
|              | Microwave        | 400  |
|              | Dishwasher       | 400  |
|              | Fridge           | 60   |
The CFD model setup was based on steady-state Reynolds-Averaged Navier Stokes (RANS) equations. The standard $\kappa-\varepsilon$ turbulence model was used since it provides stable results with good accuracy. The equations were solved using Fluent the finite-volume solver [26]. The (SIMPLE) algorithm was utilized for pressure-velocity coupling and the first-order scheme was used to discretize the equations.

3.2.3. Grid independence. The grid independence analysis was done by creating three meshes with three different sizes; coarse, medium, and fine, containing 3024492, 5307557, and 9262020 cells respectively. The mesh validation was done based on the guidelines presented by Celik et al. [27] that are based on the Richardson extrapolation (RE) method. The wind velocity that passes through the top surface of the ventilation shaft was adopted as a compression factor since it is an important variable in the investigation and relates to the functionality of the proposed ventilation method. The fine Grid Convergence Index (GCI) was 3.95% and the medium GCI was 2.37%, since the medium mesh showed an acceptable error range (Figure 4), it was adapted for the further analysis.

4. Results and discussion
The focus of the research is to reveal the functionality of the Venturi effect when applied within the proposed system. Therefore, all doors and windows were closed in the simulated scenario and only the inlets under the floor level and the top opening of the shaft were left open.

The CFD results indicate that the Venturi disc is causing the suction effect with an air change rate of 16.45 1/h. The ventilation rate varies in the different indoor spaces. The airflow speed in the sleeping area drops below 0.2 m/s which is the minimum comfort level according to ASHRAE Standard 55 [28]. The flow velocity in the spaces located on the windward side is very low and drops below 0.5 m/s, as shown in Figure 5. This is due to the pressure differences and the short distance between the floor openings and the outer façade making it insufficient for the airflow to enter the spaces located at the windward side.

![Figure 4](image1.png)  
**Figure 4.** Grid refinement of the three grid varieties based on wind velocity.

![Figure 5](image2.png)  
**Figure 5.** Indoor flow velocity in a horizontal section (left), and a vertical section (right).
Regarding indoor temperature, the airflow helped to distribute the heat load and to lead it out through the ventilation shaft due to the thermal buoyancy effect as shown in Figure 6. The simulation results show that overheating happens where there are heat sources (machines and occupants) or in the attic level because of thermal buoyancy.

![Figure 6. Indoor temperature in a horizontal section (left), and a vertical section (right).](image)

5. Conclusion
The study proofs the effectiveness of implementing the Venturi disc connected to a central ventilation shaft for “Cube houses”. Nevertheless, the under-floor inlets are partially efficient in the presented case. Further investigation is needed to eliminate the located problems, such as overheating or under-floor fresh air supply distribution and sizes. Further research will have to consider different wind directions and simulate different scenarios of closing or opening the windows in parallel to the implemented ventilation strategy.

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