EFFECT OF OBSTACLES ON THE CRAWL SPACE AIRFLOW

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Abstract

One type of building foundation is a crawl space. This system is widespread in Scandinavia, but in recent years it has been used in the Czech Republic. A crawl space is a building foundation system where there is an air gap between the building and the ground. Both the design of the structure and the proper use is important for the proper functioning of the crawl space. Any obstacle can affect the airflow in the crawl space. This paper deals with simulations of airflow and age of air with the placement of obstacles in the crawl space.

Keywords

Crawl space, wooden building, airflow, age of air

1 INTRODUCTION

There are several types of wooden buildings. These include strip foundations featuring concrete slab-on-ground, foundation on a concrete base slab or using a crawl space. This is such a foundation of a building and terrain where an air gap is created under the first floor. In recent years, crawl spaces have also been used in the Czech Republic. The design of the crawl space is important for its proper functioning, as well as its proper use. The crawl space should not be used as a cellar for storing items. Any obstruction can affect the airflow in the crawl space. There are several approaches to assessing ventilation efficiency, such as using the local ventilation index, air change efficiency, or air velocity. This assessment is also related to the age of air, which reflects the airflow pattern in the space [1]. Air age is defined as the time elapsed until the air entered the space [2], [3]. There are three methods to measure the age of air: the decay method, the source method and the pulse method. The decay method involves filling the test space with tracer gas and using a fan to mix the gas evenly to an initial concentration C_0. Then, fresh air is blown in the space. For the decay method, the mean age of the air A_p is given by the following equation (1).

$$A_p = \frac{\int_0^\infty C_p(t)\,dt}{C_p(0)}, \tag{1}$$

where $C_p(t)$ is the initial tracer gas concentration at time t and $C_p(0)$ is the initial concentration of the entire monitored space. This method assumes mixing of the air in the space. In the source method, tracer gas is added to the supply air maintaining a constant concentration C. The increase in the concentration of the tracer gas is continuously monitored. In the pulse method, small amounts of tracer gas are added to the supply air and the rise and fall of the tracer gas concentration are continuously monitored [3], [4]. There is also a method that uses the local mean air age parameter A_{cv}, see equation (2). In this method, the mixing of air with the tracer gas is only taken into account in the control volume, rather than in the entire tracer space [4], [5].

$$A_{cv} = \frac{(t_e - t_s)\,C_{av}}{C_{ts}}, \tag{2}$$

where C_{ts} is the concentration of the tracer gas over time t_s and C_{av} is the average concentration of the tracer gas in the time interval from t_s to t_e. Tracer gas methods are reliable but time-consuming. These methods cannot be used for ventilation systems with multiple rooms and several ducts. Larger ventilation systems must be addressed numerically using the Computational Fluid Dynamics (CFD) method [1], [6].

Received 24/01/2025/Accepted 07/05/2025/Published 30/09/2025 DOI 10.13164/juniorstav.2025.25049

Unventilated spaces in the structure may be created due to an obstruction that may restrict airflow. Crawl space construction is associated with the potential for mould. Moisture and debris can accumulate in vented areas and create conditions for mould development. The effect of relative humidity on microscopic growth is described by the f_{RH} factor while the f_{temp} factor describes the effect of temperature, see Fig. 1. Optimal mould growth usually occurs at an air temperature of 25–30°C with growth potentially ceasing at higher temperatures and slowing down at lower temperatures [7].

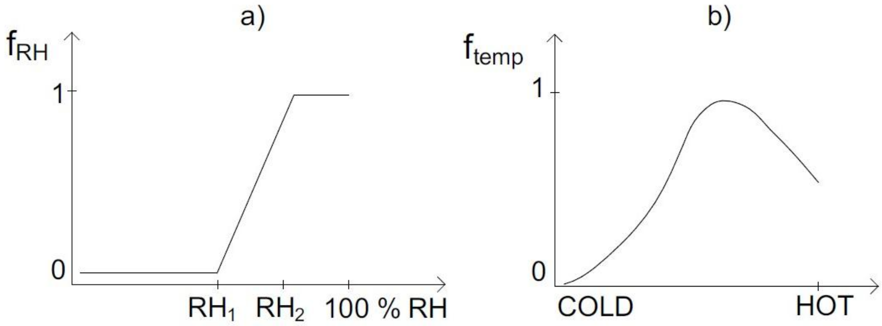

Fig. 1 a) Factor f_{RH} and b) Factor f_{temp}, redrawn according to the article [7], RH is relative humidity.

This article deals with the effect of an obstacle on airflow in a crawl space. The crawl space was evaluated using the air age. Two model situations were created:

1. The box was placed in the crawl space.
2. Objects were placed in front of the vents.

For crawl space construction, it is important to consider that storing objects in the cavity both affects airflow and can increase the fire load in the space. The increase in fire load was demonstrated in situation 1 with a box placed in the crawl space.

2 METHODOLOGY

Model for simulations

Airflow and air age were simulated for a detached house with a crawl space. The height of the crawl space is 1.20 m with dimensions of 10.680 × 6.740 m. The structure is ventilated naturally by means of 500 × 250 mm vents in the perimeter walls. The bottom of the crawl space is 750 mm below the level of the prepared ground. A central foundation wall divides the crawl space into two tracts. The small tract has an area of 23.6 m² and the large tract has an area of 36.4 m². A model of a house with a crawl space is shown in Fig. 2. The model was created in FreeCad software.

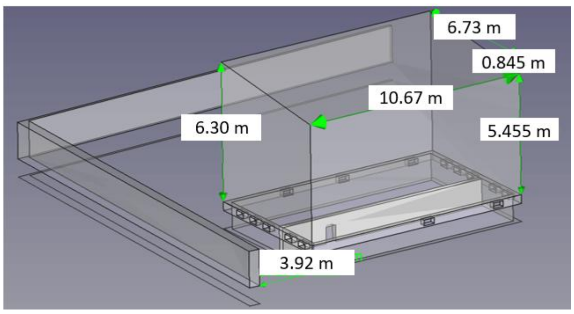

Fig. 2 Model of the detached house with a crawl space.

Two model situations were set up for the calculation, see Fig. 3. The first situation involved placing a box in a large tract. The dimensions of the box were 1.850 × 0.850 × 1.050 m. There is an air gap of 150 mm between the crawl space ceiling structure and the box. The second situation was focused on the ventilation openings of the crawl

DOI 10.13164/juniorstav.2025.25049

space. In practice, it is common to see objects placed in front of the vents. These objects can restrict air access to the crawl space or prevent it altogether. An object can be, for example, a flowerpot. Two flowerpots were placed in the model. Flowerpot 1 covered one half of the vent and flowerpot 2 covered two thirds of the vent. The arrangement of the box and flowerpots is shown in Fig. 3. The model has been simplified for simulation purposes.

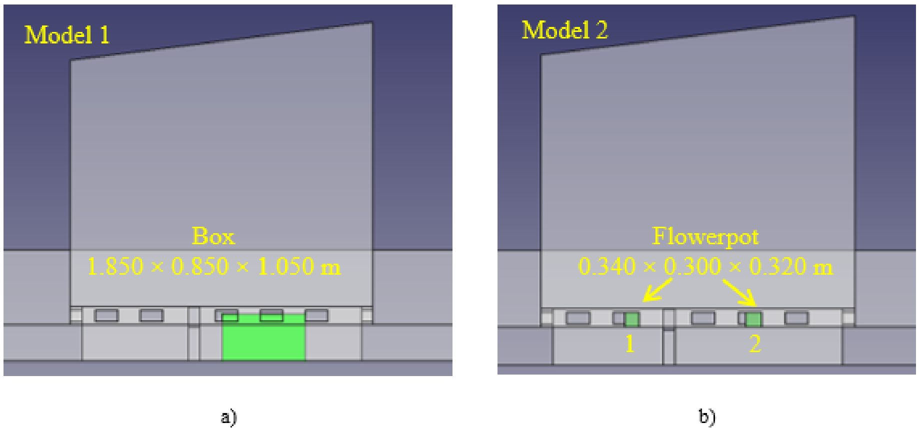

Fig. 3 Section of the detached house, a) Box in the crawl space, b) Flowerpots in front of the crawl space vents.

Simulation of airflow and air age

Simulations were calculated by OpenFOAM software. First, the airflow rate was calculated and then the air age was calculated as a post-process. The transport equation for calculating the air age is as follows (3).

$$\frac{\partial}{\partial x}(u\tau)+\frac{\partial}{\partial y}(v\tau)+\frac{\partial}{\partial z}(w\tau)=\frac{\partial}{\partial x}\left(D\frac{\partial\tau}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial\tau}{\partial y}\right)+\frac{\partial}{\partial z}\left(D\frac{\partial\tau}{\partial z}\right)+1, \tag{3}$$

where D is the diffusion coefficient in m^2/s, u is the average speed in the x direction in m/s, v is the average speed in the y direction in m/s, w is the average speed in the z direction in m/s and τ is the age of air in seconds [6], [1]. The air ages in the simulations use scalar transport and are always calculated following the flow equations. The diffusion coefficient (4) can be determined as:

$$D_{eff}=\alpha_D\cdot nu+\alpha_{Dt}\cdot nut, \tag{4}$$

where α_D is the laminar diffusion coefficient, α_{Dt} is the turbulent diffusion coefficient, nu is the kinetic viscosity, nut is the turbulent (kinematic) viscosity. However, $\alpha_D = 1/S_c$ and $\alpha_{Dt} = 1/S_{ct}$, where S_c is the Schmidt number for laminar (molecular) diffusion and S_{ct} is the Schmidt number for turbulent diffusion. It is usually assumed that $S_c = S_{ct}$ because laminar (molecular) transport is negligible in turbulent flow. In our case, $S_{ct} = 0.7$ was considered (in practice, $S_{ct} = 0.7$-0.9 is considered).

Boundary conditions:

The logarithmic wind law (5) was used for the outdoor airflow. The wind speed, given by the air pressure difference, increases logarithmically with height.

$$u(z)=\frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right), \tag{5}$$

where u is the longitudinal wind speed in $m\cdot s^{-1}$, u_* *is* the friction velocity in $m\cdot s^{-1}$, κ is the von Kármán constant and z_0 (0.05 m) is the roughness height in m aerodynamic roughness length) [8]. A simplified terrain model was used. The terrain roughness and articulation were considered within the aerodynamic roughness z_0. Kinematic viscosity was chosen for 20°C – i.e. 1.52×10^{-5} m^2/s **Inlet:** An outer boundary condition of 1.0 $m\cdot s^{-1}$ at 4.5 m above ground level was chosen to compare the crawl space model variants. **Outlet:** zero pressure (total pressure; p_0 = 0.0 Pa) was selected on the outlet side of the airflow. The boundary condition of the side walls of the computational domain was chosen to be symmetric.

DOI 10.13164/juniorstav.2025.25049

Model:

The RANS – Reynolds-averaged Navier-Stokes standard turbulent model with *k*- *ε* model was used. Model constants were: $C_\mu = 0.09$, $C_1 = 1.44$, $C_2 = 1.92$, $C_3 = 0$, $\sigma_k = 1$, $\sigma_\varepsilon = 1{,}3$. An isothermal stationary model was chosen for the simulations. The convergence limit was set to 10^{-3}. The domain was set to: *15H* downstream, *5H* upstream, and *5H* lateral distance, Fig. 4. The value of *H* is the height of the building [8], [9].

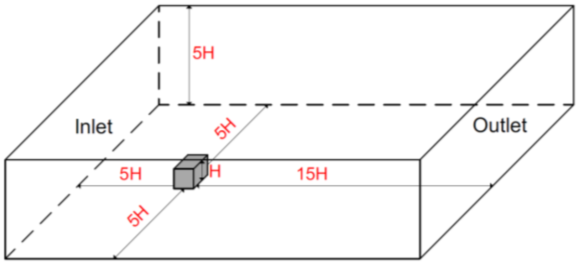

Fig. 4 Dimensions of the computational domain and boundary conditions, redrawn according to [9].

The computer network was created in the FreeCAD software (Fig. 5). The basic cell size was chosen to be 3e+03 mm. There are levels of refinement on the hexahedral grid. The network gradually becomes finer towards the building, where the cell size reaches approximately 150 mm. The network totals to 472,338 cells.

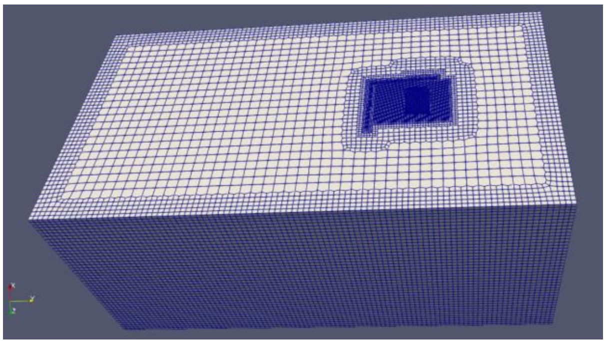

Fig. 5 Computational mesh model, FreeCAD 0.21, ParaView 5.10.1.

The model was verified using measured data by means of incandescent anemometers which were fitted into the holes in the crawl space as part of the experimental measurements. The median outdoor air velocity measurement (minimum value of 0.4 $m \cdot s^{-1}$ and maximum value of 0.9 $m \cdot s^{-1}$) was chosen as the boundary conditions for the simulation verification. These values were found at a height of 4.5 m above the ground level. The median air velocity in the vent was found to be 0.3 $m \cdot s^{-1}$at the minimum median outdoor air velocity. At the maximum median outdoor air velocity, the median vent velocity was determined to be 0.45 $m \cdot s^{-1}$. The simulated air velocity in the vent was 0.27 $m \cdot s^{-1}$and 0.61 $m \cdot s^{-1}$ [11].

Fire risk in a crawl space

The use of crawl spaces must be in accordance with the fire safety design of all buildings. Timber structures have stricter legislation requirements than structures with combustible load-bearing elements. Flammable objects in the crawl space present fire loads for which these spaces are not rated. The occurrence of a possible fire load by placing an object in the crawl space was demonstrated in model 1 - a box placed in the crawl space. In this case, the box (e.g. a wooden box) with dimensions of 1.850 × 0.850 × 1.050 m may represent a variable fire load (p_n). This is given by the equation (6).

$$p_n = \frac{\sum_{i=1}^{j} M_i \cdot K_i}{S}, \tag{6}$$

where M_i is the weight of the combustible material, K_i is the coefficient of an equivalent amount of wood, and the S is the area of the space [10].

DOI 10.13164/juniorstav.2025.25049

3 RESULTS

The age of the air in the crawl space without the box was calculated to compare the behaviour of the crawl space with the box. The results are shown in Tab. 1. The air age reading was performed at half the height of the crawl space, i.e. at 600 mm. There was a 0.22 min deterioration in the mean air age value in the large wing compared to the no-box variant. The airflow in the small wing was also affected by the location of the box in the large tract. The deterioration of the average air age was 0.19 min.

Tab. 1 Average age of air in the crawl space without/with a box in minutes (seconds).

	Tract without box reading height in 600 mm	**Tract with box reading height in 600 mm**
Small tract	4.84 (290.14)	5.03 (301.62)
Large tract	2.90 (173.97)	3.12 (187.27)

The air currents and the age distribution of the air in the crawl space are shown in Fig. 6. The effect of the box on the airflow is clear from the simulation. There is almost no airflow behind the box, and the effect is also visible in the small box (red spot). Fig. 6 and the values in Tab. 1 record the influence of only one box in the crawl space, which is 2.3% of the total crawl space volume. The deterioration of the air age values was not significant. However, in practice, we usually encounter a larger percentage of crawl space constraints where the effect on airflow may be more pronounced.

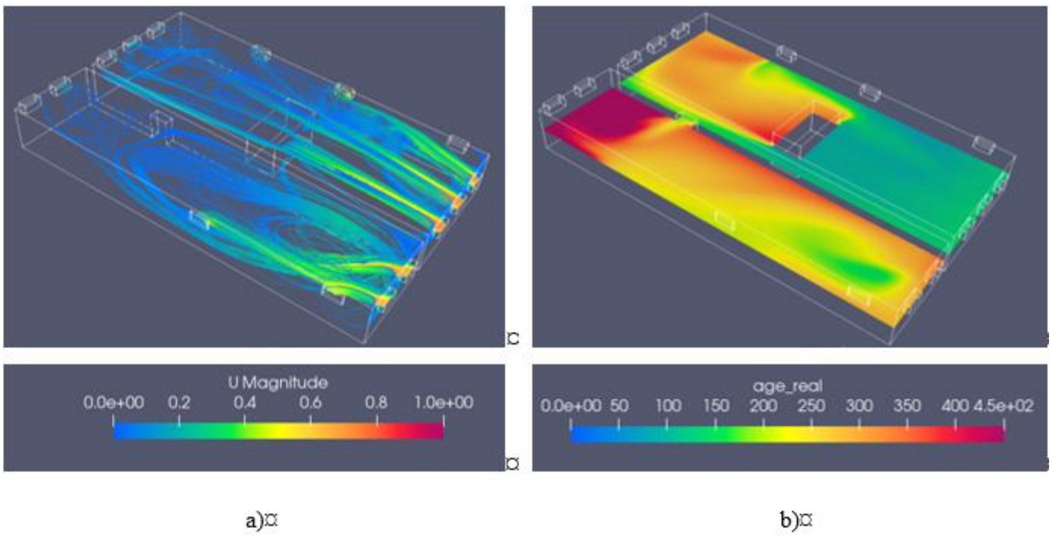

Fig. 6 Crawl space with the box, a) Airflow b) Air age.

The box located in a crawl space may present a fire load. Assuming a wooden box of 1.850 × 0.850 × 1.050 metres, the fire load was determined according to equation (6). According to this formula, the variable fire load of this one box (wooden) can be assumed as p_n = 10,322 kg/m^2. There may be several combustible objects such as this box in crawl spaces so the final p_n value can be much higher. These values may represent a significant increase in the fire load in this space, which may lead to a tightening of other requirements resulting from the final fire risk. The combustible load-bearing structures above the crawl space (ceiling/floor) must be designed for the resulting fire risk and must meet the required fire resistance.

Tab. 2 shows the air age values with covered vents according to Chapter 2 Methodology. The average air age was 6.80 min (408.08 s) i.e., a deterioration of 2.37 min in the small tract compared to the original simulation without flowerpots. The air supply was restricted to such an extent (covering the half of the vent) that air did not reach the opposite wall. There was a deterioration of 2.16 min, i.e. 4.77 min (286.20 s) in the large tract.

DOI 10.13164/juniorstav.2025.25049

Tab. 2 Average age of air in the crawl space without/with flowerpots in minutes (seconds).

	Tract without box, the height of the reading at the level of the ceiling structure	**Tract with flowerpots, the height of the reading at the level of the ceiling structure**
Small tract	4.40 (265.8)	6.80 (408.08)
Large tract	2.60 (156.5)	4.77 (286.20)

Fig. 7 shows the significant restriction of air supply to the structure. The vent covered two-thirds of the way and did not allow air to reach the structure at all.

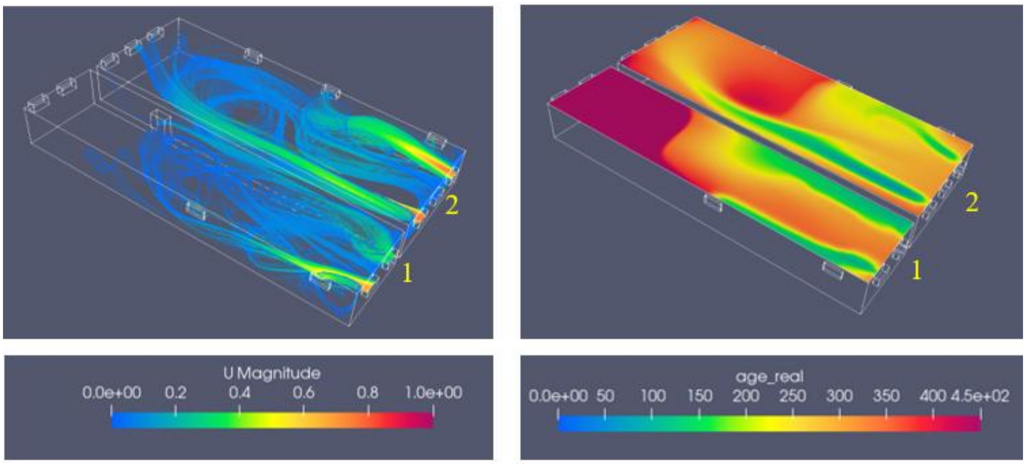

Fig. 7 Crawl space with flowerpots, a) Airflow, b) Air age.

4 DISCUSSION

The topic of a crawl space foundation structure is much discussed abroad, mainly in the countries of Northern Europe and America. Studies mainly focus on the thermal and humidity conditions of the crawl space microclimate. The vast majority of studies focus on experimental measurements in the crawl space. Examples of studies are as following:

- **Finland**

Crawl space air change, heat and moisture behaviour [11].

The study deals with monitoring of the microclimate by means of the air exchange rate. It is difficult to determine a clear value because of the many factors involved. A study by Kurnitski (2000) [11] reports values of 1.0–3.0 h^{-1} throughout the year.

On the crawl space moisture control in buildings [12].

This study approached the evaluation of the crawl space by monitoring the so-called warm (ceiling structure above the cavity with a high heat transfer coefficient $U = 0.38$ W/(m^{2}K) and the cold ceiling structure above the cavity with a low heat transfer coefficient $U = 0.20$ W/(m^{2}K). Different behaviour of the crawl spaces was found, where the cooler space was more susceptible to higher humidity, especially in the summer months.

Microbial contamination of indoor air due to leakages from crawl space: a field study [13].

The study investigated indoor environmental contamination caused by mechanical ventilation of the interior. The most frequently identified species were of the genera *Penicillium*, *Aspergillus*, and *Cladosporium*.

Review of mould prediction models and their influence on mould risk evaluation [14], *A mathematical model of mould growth on wooden material* [15].

This study demonstrates the possibility of assessing crawl space microclimate using fungal growth prediction models.

DOI 10.13164/juniorstav.2025.25049

- **Sweden**

Temperature and relative humidity measurements and data analysis of five crawl spaces [16].

The study evaluated the behaviour of five buildings with crawl spaces. The principle of comparison consisted in determining ten indicators, for example:

- The annual average temperature difference between the air in the crawl space and the outdoor air.
- The basic temperature conditions inside the crawl space.
- The time lag of the temperature in the crawl space compared to the outside air temperature,
- The number of hours per year when the air temperature in the crawl space is lower than the outside air temperature,
- The number of hours per year when the water vapour content in the crawl space is higher than the outdoor air.
- The number of hours in a year when the relative humidity is higher than 80%RH or 90%RH.

Highly insulated crawl spaces with controlled minimal ventilation [17].

The study considered the design of a crawl space with maximum thermal insulation of the envelope structures and minimum controlled air exchange. Measurements showed results of a relative humidity in the crawl space below 80%.

Experimental investigation of a crawl space located in a sub-arctic climate [18].

The crawl space microclimate was monitored under subarctic conditions. The structure was monitored with and without a dehumidifier. The relative humidity in the space with the dehumidifier was below 80%. Without a dehumidifier, the crawl space was highly susceptible to the mould growth.

Mass occurrence of Penicillium corylophilum in crawl spaces in south Sweden [19].

A total of 212 crawl space structures were analysed for mould. The genus Penicillium was the most represented.

- **Denmark**

Can crawl space temperature and moisture conditions be calculated with a whole-building hygrothermal simulation tool? [20].

The study addressed the possibility of predicting temperature and humidity conditions in the crawl space. BSim software was used. A good agreement between simulated values and measurements was found for air temperature. For relative humidity, the simulated values were approximately by 20% lower than the measured values.

Simulating the effects of solar-powered ventilation systems on energy and moisture conditions in crawl spaces [21].

The effect of crawl space design changes was simulated. These included changing the air change rate, insulation thickness and the installation of a solar ventilation system. The simulation of installing a solar ventilation system showed a positive effect in the summer.

- **USA**

Evaluation of ventilation code requirements for building crawl spaces [22].

Using CFD software, the crawl space ventilation requirements specified in the International Residential Code (IRC) were evaluated.

- **Portugal**

Controlled relative humidity in crawl spaces: a new treatment methodology [23].

The study focused on the ventilation of a crawl space at a historic building. A mechanical ventilation system, controlled by the moisture content of the air, and the hygro-regulable system, proved to be a suitable solution. The system switches on when the water vapour pressure of the outdoor environment is lower than the partial pressure of the water vapour of the air in the crawl space.

There are multiple approaches to assessing the microclimate in a crawl space, as described above. The crawl space assessment using air age that was used in this paper is not quite conventional.

DOI 10.13164/juniorstav.2025.25049

The crawl space should be ventilated to prevent the accumulation of air moisture. Unventilated areas can occur in the crawl space not only due to improper design of ventilation openings but also due to improper use of the crawl space. The crawl space should not be used as a cellar for storing objects that can severely restrict the passage of air through the structure. In this paper, the effect of placing a box in the crawl space has been highlighted using air age simulation. There was a significant restriction of airflow because of the box placed in the crawl space Deterioration was observed both in the large tract where the box was placed and in the small tract of the crawl space. The surroundings of the house should be adapted to allow air to enter the structure without any problems. It is therefore not appropriate to place any obstructions in front of the ventilation opening from the outside of the crawl space, for example, planting taller plants or trees, or placing garden pots there. A model situation has been created to illustrate the effect of placing objects in front of the vents. The first flowerpot covered the ventilation hole from one-half (1/2) and the second flowerpot from two-thirds (2/3). The simulations showed a small deterioration of 2.37 min compared to the simulation without flowerpots. In the large tract, there was a deterioration of 2.16 min, i.e. 4.77 min (286.20 s). The vent covered 2/3 of the way and did not allow air to enter the structure at all. The age distribution of air without obstacles in the crawl space is shown in the publication by Pobucká et al. (2024) [24]. In the crawl space, the effect of the box was to increase the air age by 4% in the small tract and 8% in the large tract. It cannot be said that only one box was placed in the crawl space. If more boxes were placed there, more air ageing could occur in the crawl space. Placing objects in front of the vents increased the air age in the small crawl space by 54% and in the large crawl space by up to 83%. A simplified model of the building was used to calculate the age of the air, assuming a completely flat surrounding terrain. Furthermore, the simulation was calculated stationary with the RANS model with turbulent k- ε model. The standard k- ε model is the most widely used turbulent model in practice. The simulation results could be refined by more detailed modelling of the surrounding terrain with the inclusion of a non-stationary field. Natural obstacles such as trees are not considered in the model. Furthermore, the roughness of the obstacle in the crawl space was not considered. The aim is to save computational cells = computational complexity and to highlight the placement of the objects in the crawl space. The most accurate would be to use so-called large eddies (LES) such as Smagorinski or Wale. However, this model needs an extremely fine mesh where the computational and time requirements are large.

The crawl space should also be assessed as part of the fire safety design of the building. These spaces usually are not specifically designed and are considered without any stored objects that would impede their functionality. Placing objects in the crawl space may also present a potential fire risk. The exact limitations and requirements for crawl spaces are currently not directly specified in the Czech Republic. The determination of the requirements for these spaces and their associated structures should be based on the overall use of the space according to the fire safety design.

5 CONCLUSION

This paper deals with the simulations of airflow and air age in a crawl space. The aim was to highlight the deterioration of airflow due to crawl space obstacles commonly encountered in practice. The obstacles can be objects stored in the crawl space or in front of the vents (in practice, e.g. flowerpots or bushes). These obstacles may cause deterioration of the microclimatic conditions in the crawl space. Air age simulation has proven to be a useful tool to initially highlight critical areas in the crawl space. For example, mould spores, dirt or moisture can accumulate in the places where air stays the longest. If adverse conditions persist for long periods of time, the structure, especially its wooden parts, can be degraded. Deterioration of conditions in the crawl space by the placement of objects can also affect the fire safety of the structure. These objects increase the fire load in the crawl space.

Acknowledgements

The research was supported by the Brno University of Technology, Faculty of Civil Engineering – Junior Specific Research No. FAST-J-23-8251 and FAST-S-24-8620.

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DOI 10.13164/juniorstav.2025.25049