Radon Sub-slab Suctioning System Integrated in Insulating Layer

Torben Valdbjørn Rasmussen[1]

Abstract

A new principle for radon protection, using a system containing a horizontal grid of air ducts pressurised within the rigid insulation material, was presented. The principle was based on the principles for pressure reduction of the zone underneath the ground floor construction. A new element of prefabricated lightweight elements were introduced and demonstrated. The principle was demonstrated on a concrete ground slab floor with a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. The thermal insulation and the capillary-breaking layer consisted of a rigid insulation material. The new solution integrates the capillary-breaking layer and a pressure reduction zone, denoted the radon–suctioning layer, in one element. The new solution introduces the radon-suctioning layer as a horizontal grid of air ducts with low pressure to catch air and radon from the ground. The new principle was shown to be effective in preventing radon from polluting the indoor air by introducing low pressure in the horizontal grid of air ducts. A lower pressure than the pressure inside the building must be established. The element was integrated into the insulation material of the ground slab floor. The element and the insulation material were made of expanded polystyrene. The new element can be handled by one man on site.

Keywords: Radon, Protection, Sub-slab, Suctioning, Insulating

1. Introduction

Radon is a radioactive noble gas that develops as a result of the decay chains of uranium and thorium, Clavensjö and Åkerblom (2004). When radon decays into different radon daughters, it generates alpha, beta and gamma rays. These rays are harmful to human beings. Radon originates in the ground and is the primary source of natural radiation in most countries, Danish Enterprise and Construction Authority (2007). Therefore the geological character of the ground, on which a building is situated, sets the level for how high the radon concentration of the indoor air can become. Radon mainly penetrates into a building by air infiltration from the ground through cracks or other unintended openings in the ground construction, Lehmann, Landfermann, Junkert and Schöppler (2001).

[1] Senior Researcher, Department of Construction and Health, Danish Building Research Institute, Aalborg University, A.C Meyers Vænge, 2450 København SV, Denmark; tvr@sbi.aau.dk

In 2009, the World Health Organization, WHO, recommended that requirements to the accepted maximum radon concentration in the indoor air should be tightened from 200 Bq/m^3 to 100 Bq/m^3. The new recommendations are a result of WHOs evaluation that radon is responsible for 3-14% of lung cancer incidents, depending on the average radon exposure in different countries, Zeeb and Shannoun (2009). These findings showed radon as the second-largest cause of lung cancer; smoking is still the principal cause. Radon exposure must be taken seriously in the fight against radon-induced lung cancer due to the large number of people that are exposed daily in buildings and especially in residential buildings, Zeeb and Shannoun (2009), as a large number of residential buildings are built with a slab on ground. An investigation shows that if people spend their whole life in a building with an average radon concentration in the indoor air exceeding 200 Bq/m^3, their risk of getting lung cancer is higher than 1%, Andersen et al. (1997). This is far too high and higher than what in other contexts is an acceptable single-factor risk. Ensuring a good quality of the indoor air includes a focus on radon and methods for controlling the radon concentration in the indoor air.

In 2010, the requirements recommended by WHO were implemented in the Danish Building Regulations. The Danish Building Regulations now stipulate a maximum radon concentration of 100 Bq/m^3 in the indoor air in all new buildings. For existing buildings, simple and cheap actions are recommended if the concentration ranges between 100 Bq/m^3 and 200 Bq/m^3 in the indoor air; however, if the radon concentration exceeds 200 Bq/m^3, immediate intervention is necessary and more efficient efforts and improvements are recommended in order to lower the concentration of radon in the indoor air, Danish Enterprise and Construction Authority (2010). The first radon provisions were introduced in the Danish Building Regulations in 1995, Danish Enterprise and Construction Authority (1995).

Solutions to prevent radon from polluting the indoor air are traditionally based on a combination of three different principles: i) establishing a protective layer against radon by using airtight materials and membranes, ii) introducing pressure reduction of the zone underneath the ground floor construction, and iii) providing effective dilution of the indoor air with outdoor air. Of these principles, ii), pressure reduction is considered by far the most efficient. Pressure reduction requires a permeable radon–suctioning layer. Shingles, pebbles or coated ceramic pellets are permeable materials traditionally used for creating a capillary-breaking layer. However, today the capillary-breaking layer is made of rigid insulation material. Therefore, new solutions are needed that create a permeable layer within the lower capillary-breaking zone of the rigid insulation material in the ground slab floor.

The paper presents a new prefabricated lightweight element designed to reduce and control the pressure reduction of the zone underneath the ground floor construction. The effect of the element was demonstrated on a ground slab floor, which was constructed of a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. The thermal insulation and the capillary-breaking layer consisted of a traditional rigid insulation material of expanded polystyrene, EPS. The new element integrates the capillary-breaking layer and the pressure reduction zone, denoted the radon–suctioning layer, in one element. The solution intends to introduce a horizontal grid of air ducts pressurised to suction air and radon from the ground. Results showing the radon-suctioning layer and the principles for its establishment within the rigid insulation material are presented. Equations to predict the airflow within the ground slab floor were developed. A finite difference program was used to calculate the airflow. Simulations of airflow within the rigid insulation material were shown for a number of pressure differences between the pressure indoor and the pressure in the air ducts. Simulations of the airflow within the rigid insulation material were carried out for both low and high quality of EPSs combined with flooring that is more and less airtight. Results were used to provide directions on how to obtain an effective radon protection using a system containing a horizontal grid of air ducts pressurised within the rigid insulation material of a traditional ground slab floor.

2. Measures to limit radon indoors

Solutions to prevent radon from polluting the indoor air and to limit and control radon concentration in the indoor air are based on a combination of three different principles: 1) A layer protecting against radon infiltration established by using airtight materials and membranes, 2) Pressure reduction of the zone underneath the ground floor construction, and 3) Effective dilution of the indoor air with outdoor air. The three principles are shown in Figure 1.

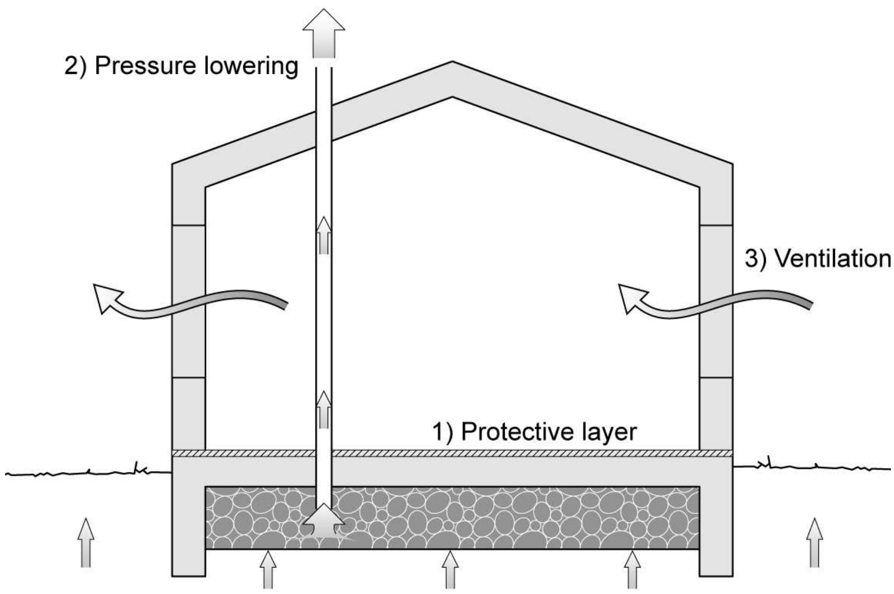

Figure 1: By combining three principles, the radon penetration and concentration indoors can be controlled. 1) Establishing a protective layer that prevents air infiltration from the ground. 2) Lowering the pressure difference over the floor construction of the building facing the ground. 3) Diluting the indoor air in the building with outdoor air.

3. Pressure lowering

The most effective way of preventing air that may contain radon from infiltrating from the ground into a building is considered to be a radon-suctioning system, Valdbjørn Rasmussen (2010). The principle is that the pressure is lowered in the zone underneath the ground slab floor of the building. The pressure difference can be up to 10 MPa between the interior of the building and underneath the ground slab floor. This pressure difference can be equalised by establishing a connection between the atmosphere and a highly permeable layer underneath the building. In such a construction, the pressure difference, over the floor construction of the building facing the ground, will decrease and result in a decrease of the amount of ground air that can infiltrate. The radon-suctioning system can either be passive or active, i.e. creating suction through the stack effect only or creating suction by means of mechanical ventilator. A pipe can be led directly from the radon-suctioning layer and above the roof. Suction is introduced through the pipe to the radon-suctioning layer.

4. Theory

The Heat2, HEAT2 (2010), finite difference program was used for the pressure equalisation calculations. It was assumed that the pressure difference was so low that the air would not be compressed. Additionally, it was assumed that the speed of the air through the materials of the ground slab floor was within the range of a laminar airflow. Furthermore, the individual materials were porous and homogeneous. Under these conditions, air flowing through a porous material can be described mathematically in the same way as a stationary thermal conductance problem. A stationary thermal conductance problem is described by:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)=0 \tag{1}$$

Where, T is the temperature and k_x, k_y, k_z are the thermal conductance in the x, y, z axes, respectively.

The differential equation, Equation (1) expresses that the total effect that is supplied to and removed from a control volume is equal to zero.

The result of a thermal conductance problem is a temperature distribution within the analysed element. From the temperature distribution, the effect that needs to be removed or absorbed through the borders, to maintain the stationary temperature distribution can be determined. In the same way, the air pressure distribution can be calculated and the amount of air that needs to be removed or absorbed through the borders, in order to maintain the stationary pressure distribution, can be determined for porous materials. A stationary pressure distribution problem is described by:

$$\frac{\partial}{\partial x}\left(q_x \frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(q_y \frac{\partial P}{\partial y}\right)+\frac{\partial}{\partial z}\left(q_z \frac{\partial P}{\partial z}\right)=0 \tag{2}$$

Where, P is the pressure and q_x, q_y, q_z are the pressure distribution in the x, y, z axes, respectively.

Using the finite difference program Heat2, HEAT2 (2010), for air-pressure calculation, the temperature was replaced by the air pressure, the thermal conductance was replaced by the air permeability and the effect was replaced by the amount of air per time. A stationary air pressure problem described by Equation (2), then expresses that the amount of air that is brought in and the amount of air brought out of the control volume is equal to zero.

Using the Heat2 program and a PC for the pressure analyses, the input data for the thermal conductance values were replaced by the air-permeability values and the prescribed temperatures were replaced by the prescribed air-pressure values. Calculations were performed to reach air-pressure equilibrium between the air pressure indoors and the air pressure in the ground. For the state of pressure equilibrium, the amount of air per time unit was determined, which it was necessary to remove or absorb through the upper surface of the concrete slab facing the indoor environment.

Usually the air permeability of a material is given as the resistance known as the Z-factor with the unit (h m^2 Pa)/g describing a specific building component of a specific thickness. For these calculations, the air permeability must be determined as the reciprocal value of the Z-value multiplied by the thickness of the building component.

5. Radon Sub-slab Suctioning System

The highly permeable and capillary-breaking layer underneath the building often consists of i.e. shingles, pebbles or coated ceramic pellets but can also be a layer of EPS with a horizontal grid of air ducts.

5.1 Material

The prefabricated element was made of EPS to form an element that could be used as the capillary-breaking layer and the radon–suctioning layer integrated in one element. The air permeability was 0.0144 g/(m h KPa) for a EPS with a density of 20 kg/m^3 and 0.0054 g/(m*h*KPa) for a EPS with a density of 32 kg/m^3, respectively.

5.2 Design

The prefabricated element was produced as units of 600 mm in length and 400 mm in width and 50 mm in thickness. A horizontal grid was cut out and removed from the upper surface of the element, thus creating air ducts 30 mm wide and 30 mm deep with a centre distance of 100 mm. At the border towards the upper surface of the element, an air duct 15 mm wide and 30 mm deep was cut out and removed. The element is shown in Figure 2.

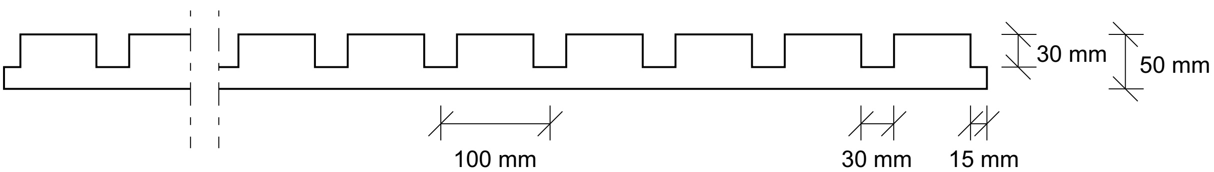

Figure 2: The new prefabricated element made of EPS.

6. Modelling

Calculations of the airflow through the ground slab floor were made using a PC and the finite difference program Heat2, HEAT2 (2010), version 7.0. Calculations were performed with a constant air pressure indoors and a constant air pressure in the ground. Heat2 was used to calculate the amount of air passing through the upper surface of the concrete slab, using a constant air pressure above the concrete slab representing the air pressure inside and a constant air pressure in the air ducts of the element combined with a constant air pressure in the ground underneath the ground slab floor. The air pressure in the ground underneath the ground slab floor was 101 328.6 Pa. An adiabatic interface is bordering to the right and to the left of the model. The ground slab floor is shown in Figure 3 and the model used for the calculations is shown in Figure 4.

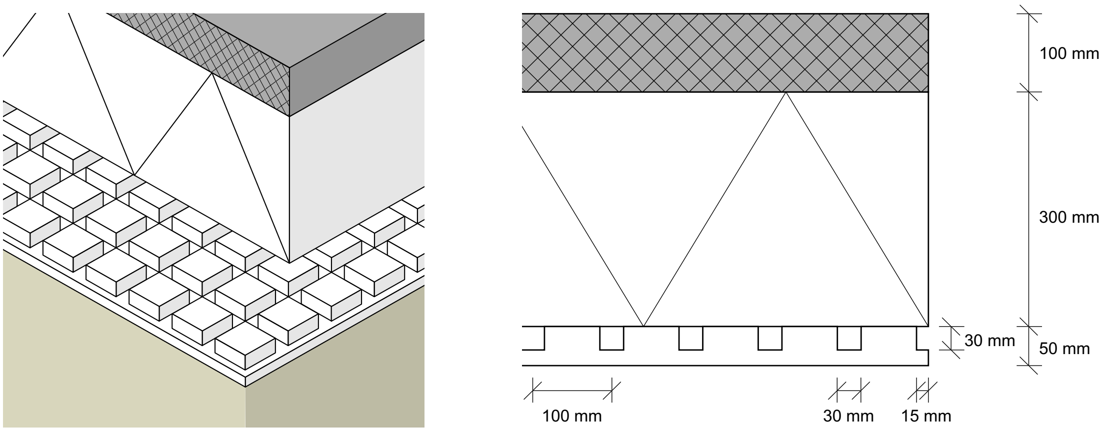

Figure 3: The ground slab floor was constructed of a concrete slab on top of a thermal insulation layer fitted above the new element. The combined capillary-breaking layer and the radon-suctioning layer are shown as the new integrated element. Left; ground slab shown in perspective view. Right; ground slab shown in sectional view.

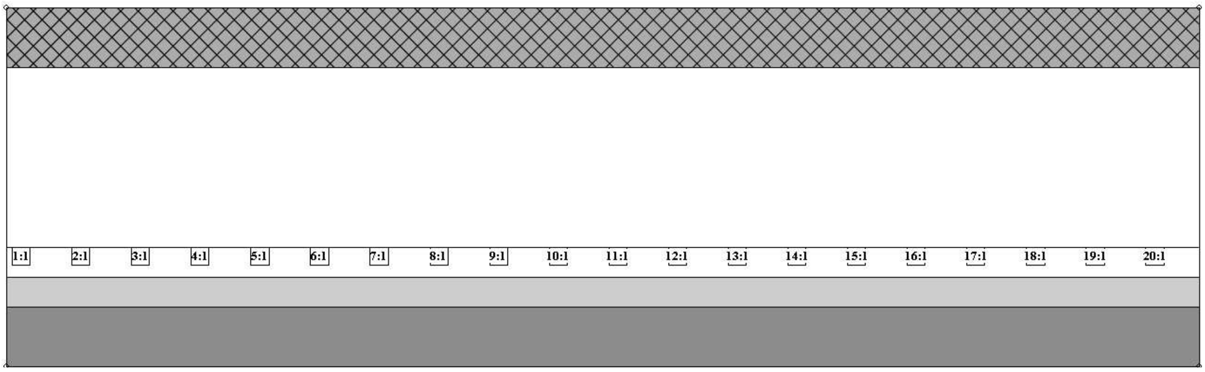

Figure 4: The model used for calculations. The model includes a concrete slab on top of a thermal insulation layer above the new element mounted on stable ground. The horizontal grid of air ducts are shown as square units that are numbered 1:1 to 20:1. Usually the top-soil layer is removed from an area covering the area of the building. The excavated area is then covered with gravel to level the excavated area. Included in the model were 50 mm of gravel and 100 mm of soil. The model was 2.0 m in length.

7. Results

For the calculations, the air permeability of the concrete, the soil and the gravel were 0.018 g/(m h KPa), 0.36 g/(m h KPa) and 0.576 g/(m h KPa), respectively. The atmospheric pressure was 1 atm equal to 101 325 Pa. For the calculations the pressure inside were 101 321.25 Pa, 101 323.24 Pa and 101 324.85 Pa, respectively, Bovbjerg and Gunnarsen (2008), in combination with a number of different pressure levels in the air ducts of the radon sub-slab suctioning system, between 101 325.00 Pa and 101 320.00 Pa. The thickness of the concrete and the layer of thermal insulation were 100 mm and 300 mm, respectively. The thermal insulation was EPS with the air permeability of 0.0144 g/(m h KPa). The radon sub-slab suctioning system was of EPS with an air permeability of 0.0144 g/(m h KPa). Results are shown in Figure 5.

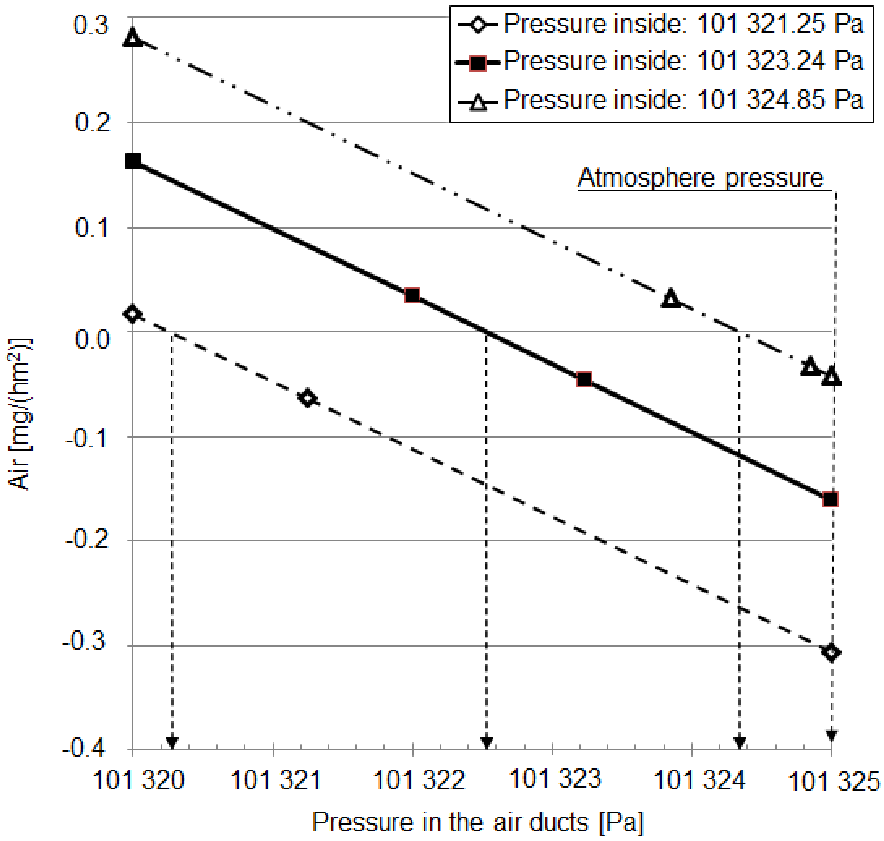

Figure 5: Amount of air passing through the upper surface of the concrete slab in milligram per hour per square metre. A positive number for the amount of air represents air moving through the ground slab floor towards the air ducts.

Calculations were repeated assuming the concrete to be less air tight with an air permeability of 0.36 g/(m h KPa). In addition, the calculations were repeated for a more dense EPS with a density of 32 kg/m^3 and with an air permeability of 0.0054 g/(m h KPa). The air permeability was changed individually. For the calculations, the atmospheric pressure was 1 atm equal to 101 325 Pa. The pressure inside was 101 323.24 Pa in combination with a number of different pressure levels in the air ducts of the radon sub-slab suctioning system, between 101 325.00 Pa and 101 320.00 Pa. The thickness of the concrete and the layer of thermal insulation were 100 mm and 300 mm, respectively. Results are shown in Figure 6.

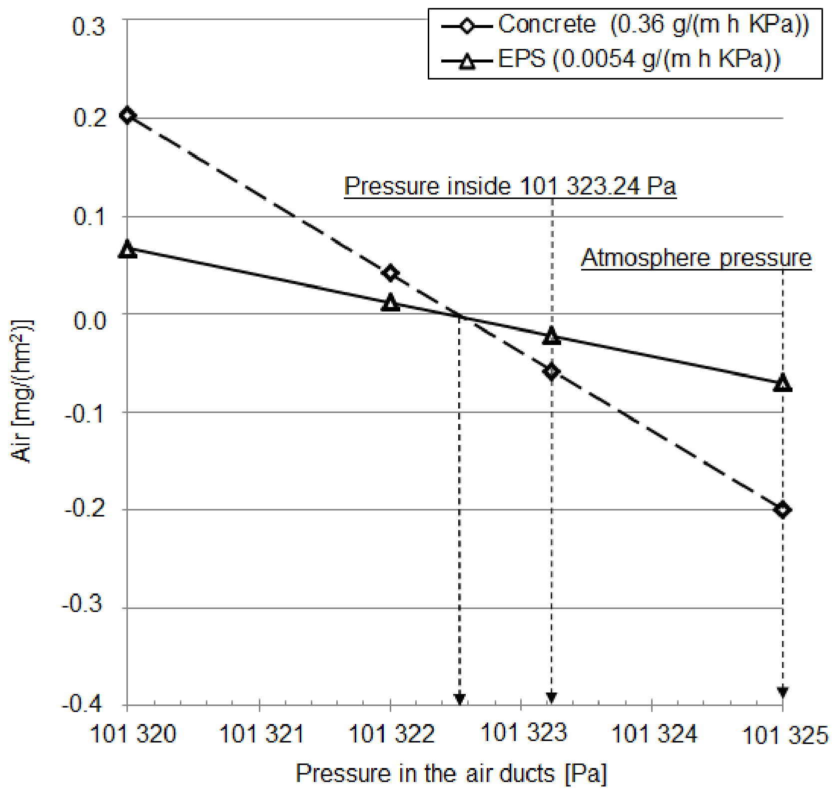

Figure 6: Amount of air passing through the upper surface of the concrete slab in milligram per hour per square metre. A positive number for the amount of air represents air moving through the ground slab floor towards the air ducts. Calculations were made assuming a less air tight concrete with an air permeability of 0.36 g/(m h KPa) and assuming a more dense EPS with a density of 32 kg/m^3 with the air permeability of 0.0054 g/(m h KPa), respectively.

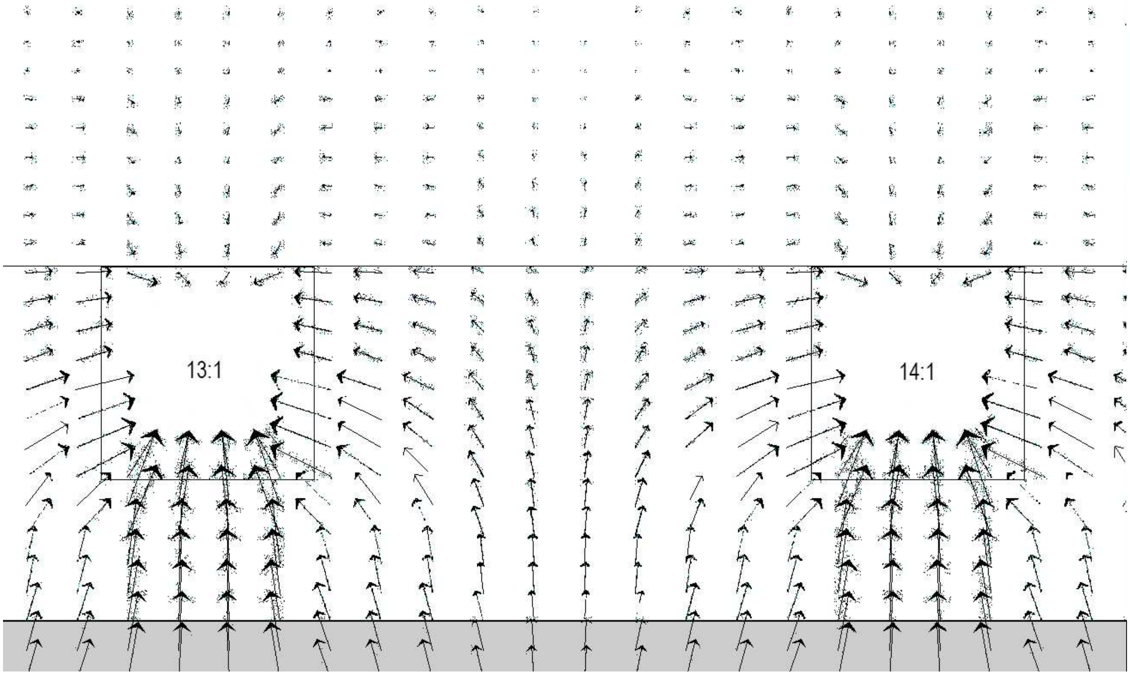

Figure 7: The calculated airflow around air duct No. 13:1 and No. 14:1 in the radon sub-slab suctioning system. The radon sub-slab suctioning system made of EPS is shown mounted on a layer of gravel and underneath the thermal insulation of EPS.

The air permeability of a the concrete was 0.018 g/(m h KPa). The pressure inside was 101 323.24 Pa and the pressure in the air ducts of the radon sub-slab suctioning system was 101 320.00 Pa. The thermal insulation was EPS with an air permeability of 0.0144 g/(m h KPa). The radon sub-slab suctioning system was made of EPS with an air permeability of 0.0144 g/(m h KPa). Arrows show the airflow and the length of the arrows visualizes the relative volume of air flowing.

The calculated air flow in the radon sub-slab suctioning system of EPS and the bordering thermal insulation layer of EPS around air duct No. 13:1 and No. 14:1 is shown in Figure 7. For the calculations, the air permeability of the concrete, the soil and the gravel were 0.018 g/(m h KPa), 0.36 g/(m h KPa) and 0.576 g/(m h KPa), respectively. The atmospheric pressure was 1 atm equal to 101 325 Pa. The pressure inside was 101 323.24 Pa and the pressure in the air ducts of the radon sub-slab suctioning system was 101 320.00 Pa. The thickness of the concrete and the layer of thermal insulation were 100 mm and 300 mm, respectively. The thermal insulation was made of EPS with an air permeability of 0.0144 g/(m h KPa). The radon sub-slab suctioning system was made of EPS with an air permeability of 0.0144 g/(m h KPa). Arrows show the airflow and the length of the arrows visualizes the relative volume of air flowing.

8. Discussion

A new prefabricated lightweight element that can be used to reduce the air pressure in the zone underneath the ground floor construction has been introduced. The new element is made of expanded polystyrene, EPS. The element is produced as one integrated element consisting of units of 600 mm in length and 400 mm in width and 50 mm in thickness. A horizontal grid of air ducts is cut in the upper surface of the element, thus creating air ducts 30 mm wide and 30 mm deep with a centre distance of 100 mm. Along the edge of the upper surface of the element, air ducts 15 mm wide and 30 mm deep were cut and the EPS removed. The element is designed to be handled on site by one man.

Traditionally, a ground slab floor is used that is constructed of a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. The thermal insulation layer consists of a rigid insulation material. The capillary-breaking layer consists of either a layer of a rigid insulation material on a thin layer of gravel used to level the excavated area or a layer of i.e. shingles, pebbles or coated ceramic pellets. The new element makes it possible to combine the capillary-breaking layer and the radon–suctioning layer in one integrated element of EPS. The most effective way of preventing radon from infiltrating from the ground into the indoor air of a building is to lower the air pressure of the zone underneath the ground floor construction. By lowering the air pressure of the zone underneath the ground floor construction, the pressure difference over the floor construction can be lowered. A pipe can be led directly from the radon-suctioning layer to above the roof. Suction is introduced to the radon-suctioning layer through the pipe. The suction can either be passive or active i.e. creating suction through the stack effect only or creating suction by means of mechanical ventilator. A horizontal grid serving as air ducts in a layer of EPS could be used as a permeable layer to be used as a radon-suctioning layer underneath the floor construction of a building. The novel element can be used to lower the pressure difference over the floor construction of the building facing the ground, and in this way prevent ground air from infiltrating from the ground, and additionally prevent the risk of radon polluting the indoor air.

Calculations of the airflow through a ground slab floor were made using a PC and a finite difference program. Mounted on stable ground, the ground slab floor was constructed of a concrete slab on top of a thermal insulation layer and fitted above the new element that works as the combined capillary-breaking layer and the radon-suctioning layer. Calculations were performed with a constant indoor pressure and a constant pressure in the ground. Calculations of the airflow and movements of the air are shown in Figure 7. Arrows show the direction of the airflow and the length of the arrows visualises the relative volume of air flowing. The airflow and the direction of the moving air in the ground floor construction are shown. The airflow in the area around individual air ducts in the radon sub-slab suctioning system is shown in detail for an air pressure difference of 1.76 Pa between the interior and the exterior of the building. The air pressure in the radon sub-slab suctioning system is 3.24 Pa lower than inside the building. Arrows show the movement of air within the ground floor construction. Air is shown to move from the interior of the building to the radon sub-slab suctioning system.

Calculating the amount of air passing through the upper surface of the concrete slab shows that the air pressure in the air ducts of the radon-suctioning layer needs to be lower than the pressure inside in order to prevent radon and ground air to infiltrate from the ground through the floor construction. Figure 5 shows that the amount of air passing through the upper surface of the concrete slab is approximately zero for an indoor air pressure equal to 101 321.25 Pa, 101 323.24 Pa and 101 324.85 Pa and an air pressure in the air ducts equal to 101 320.28 Pa, 101 322.53 Pa and 101 324.35 Pa, respectively for an outdoor air pressure of 101 325 Pa. The needed pressure difference over the ground floor construction decreases as the air pressure inside gets nearer the outdoor air pressure.

Assuming a less airtight concrete slab and calculating the amount of air passing through the upper surface of the concrete slab shows that the air pressure in the air ducts of the radon-suctioning layer needs to be at the same level as the earlier calculations presented here to prevent radon and ground air from infiltrating from the ground through the floor construction. Figure 6 shows that the amount of air passing through the upper surface of the concrete slab is approximately zero for an indoor air pressure equal to 101 323.24 Pa and an air pressure in the air ducts equal to 101 322.53 Pa for an outdoor air pressure of 101 325 Pa. Assuming the use of an EPS with a higher density resulting in a material with a structure more dense and more airtight and calculating the amount of air passing through the upper surface of the concrete slab shows that the air pressure in the air ducts of the radon-suctioning layer needs to be at the same level as the earlier calculations to prevent radon and ground air to infiltrate from the ground through the floor construction. Figure 6 shows that the amount of air passing through the upper surface of the concrete slab is approximately zero for an indoor air pressure equal to 101 323.24 Pa and an air pressure in the air ducts equal to 101 322.53 Pa for an outdoor air pressure of 101 325 Pa. However, as the ground floor construction gets more airtight, less air passes through the upper surface of the concrete slab for an air pressure introduced in the air ducts of the radon-suctioning layer.

The air pressure difference between the interior of a building and the radon sub-slab suctioning system can be controlled by controlling the air pressure in the horizontal grid of air ducts in the radon-suctioning layer. By controlling the air pressure in the horizontal grid of air ducts penetration of air and radon from the ground can be avoided. In this way the radon sub-slab suctioning system will suck up air and radon from the ground to be released to the atmosphere. One should be careful to release the ground air to the atmosphere at locations where it will not be drawn into the building with outdoor air for ventilation.

If the pressure underneath the building is lower than the pressure inside it, air might be drawn through the concrete slab from the inside. This might be a concern if there is a risk of warm, humid air being drawn down through the floor construction, where it is cooled down in organic material resulting in risk of mould growth. However, this is not a concern for the considered floor construction.

9. Conclusion

A new element made of expanded polystyrene, EPS, which can create the radon sub-slab suctioning system has been introduced. The element can be used to reduce the air pressure in the zone underneath the ground floor construction and is integrated in the insulation layer. The element is produced as one integrated element consisting of units that can be handled on site by one man. Elements are mounted on a levelled stamped stable basis of an excavated area of a building. The layer of elements introduces the radon-suctioning layer as a horizontal grid of air ducts with low pressure to catch air and radon from the ground. The principle is shown to be effective in preventing radon from polluting the indoor air by introducing low pressure in the horizontal grid of air ducts. The principle has been demonstrated on a ground slab floor, constructed of a concrete slab on top of a thermal insulation layer above a capillary-breaking layer mounted on stable ground. In this way, the element is integrated into the insulation material of the ground slab floor.

The principle has been demonstrated carrying out pressure equalisation calculations using a finite difference program. For the pressure equalisation calculations, it is assumed that the pressure difference is so low that the air will not be compressed. Additionally, it is assumed that the airflow through the materials of the ground slab floor is in the range of a laminar airflow. Furthermore, it is assumed that the individual materials are porous and homogeneous. Results show that a pressure that is lower than the pressure inside the building must be introduced creating an efficient radon sub-slab suctioning system. The needed pressure difference over the ground floor construction decreases as the air pressure inside gets nearer the outdoor air pressure.

By lowering the air pressure of the zone underneath the ground floor construction, the pressure difference over the floor construction can be lowered. A pipe can be led directly from the radon-suctioning layer and above the roof. Suction is introduced to the radon-suctioning layer through the pipe. The suction can either be passive or active i.e. creating suction through the stack effect only or creating suction by means of mechanical ventilator. Only if a minor reduction of the pressure is needed in the radon-suctioning layer, a passive suction system created by the stack effect can be used. One should be careful not to release the ground air to the atmosphere in places where it will be drawn into the building with outdoor air for ventilation.

Calculations have been carried out for an indoor air pressure equal to 101 321.25 Pa, 101 323.24 Pa and 101 324.85 Pa, an outdoor air pressure of 101 325 Pa and an air pressure in the soil underneath the ground slab floor of 101 328.6 Pa.

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