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Achieving airtightness of the building envelope in practice: an instrument to comply with the Kyoto Protocol

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ABSTRACT: The paper focuses on the principles and the importance of achieving an airtight building envelope. The paper discusses methods for establishing an airtight shell that encases the heated interior of a building and prevents air penetration through unforeseen leakages in the thermal envelope, methods for air permeability measurements, and how airtightness can be achieved in practice. In Denmark buildings consume a large share of the total national energy production for heating and comfort. A government development initiative has step-by-step increased insulation requirements over the last couple of years. With regard to a better heat-insulated building envelope, the importance of an airtight building envelope becomes higher in relation to the total energy consumption. This leads to requirements to the airtightness of the building envelope in the Danish Building Regulations as an instrument to comply with the national obligations related to the Kyoto Protocol. Furthermore, air that seeps in and leaks out through unforeseen leakages in the building envelope will result in a less efficient heat exchanger, if used for the ventilation system of the building and an increased risk of mould growth within the building envelope. However, a building must be ventilated - fresh air must be provided to the building in a way that satisfies the human needs for hygiene and comfort.

1 INTRODUCTION

1.1 *Kyoto Protocol obligations*

The Kyoto Protocol entered into force on 16 February 2005 and obligates signatory industrialised countries to reduce their emissions of greenhouse gases in the period between 2008 and 2012. As part of the internal distribution of obligations within the EU, it was decided that Denmark must reduce its emissions of greenhouse gases by 21% compared with 1990 emissions. In 2005 the Danish Government presented an action plan with the aim of promoting significant results in the energy field. This action plan outlines goals for the Danish energy sector in the years leading up to 2025. In addition, the action plan also signals that long-term efforts must be made in order to keep energy consumption at current levels in the run-up to 2025.

1.2 *Actions in the building environment*

The action plan focuses particularly on energy consumption in buildings, where the largest and most cost-effective potential for energy savings lies. It is estimated that buildings consume nearly 50% of the Danish energy production for heating and comfort. It is known that there is a direct connection between an airtight building envelope and a low consumption of energy in a building. Air penetration through unforeseen leakages in the building envelope increases the energy consumption for heating and comfort. It is estimated that air that seeps in and leaks out through unforeseen leakages in the building envelope increase the energy consumption by 20 to 30% compared with an airtight building envelope.

1.3 *Airtightness: a property of the building envelope*

Airtightness is an important property of building envelopes. It is a key factor for determining air permeability and related wall-performance properties such as heat loss, indoor air quality, maintainability and moisture balance.

Air leakage through the building envelope contributes to ventilation, heating and cooling costs and moisture migration. Airtightness is the most important property of building envelopes to understanding ventilation. It is quantified in a variety of ways, all of which typically go under the heading of "air leakage". Airtightness is important from a variety of perspectives, but most of them relate to the fact that airtightness is the fundamental building property that most impacts infiltration as well as exfiltration, generally recognised as the movement of air through leaks, cracks or other unforeseen openings in the building envelope.

There is a direct connection between an airtight building envelope and the energy consumption for heating and comfort for a building.

2 ESTABLISHING AN AIRTIGHT SHELL

To control the airtightness of a building, it is recommended that an airtight shell is established. The airtight shell is defined as that shell which encases the heated interior of a building and prevents air penetration through unforeseen leakages in the thermal envelope, see Figure 1. Typically the airtight shell follows the building envelope, which consists of lightweight or heavy weight building components like wood-stud walls and concrete wall elements, respectively, combined with windows, doors, ceilings, and roof and floor-slab constructions. Critical locations in the shell are situated where building components are placed in staggered levels, in joints between building components and at conduits, where installations are brought into a building. For lightweight building components such as wood-stud walls and ceilings, located in the North European countries, the airtight shell can be established by a 0.15 to 0.2 mm polyethylene foil that also serves as the vapour barrier located within the insulation layer, e.g. placed between the wood trusses and the laths, see Figures 5 and 6. When a polyethylene foil is used as a vapour barrier as well as an airtight shell, it is crucial that the foil is located at the warm side of the dew point and that the joints between the sheets of foil and joints facing other building components are airtight and securely fixed. Heavyweight building components such as concrete wall elements are normally considered to be airtight in themselves; otherwise an airtight shell must be established e.g. by a layer of plaster.

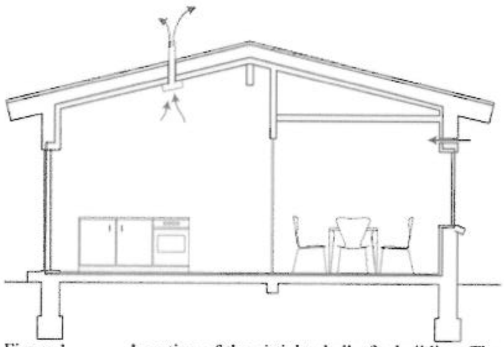

Figure 1. Location of the airtight shell of a building. The shell follows the building envelope, which consists of lightweight or heavyweight building components like wood-stud walls and concrete wall elements, respectively, combined with windows, doors, ceilings, and roof and floor-slab constructions.

It is crucial that the joints are secured and fixed in a way that they maintain their airtight properties, and that they are not damaged or decompose, during their service life. This entails a great deal of focus on how to establish the airtight shell on site designed during the design phase of a building.

To prevent air penetration through unforeseen leakages in the building envelope, a more efficient heat exchanger can be installed, if it is used for the ventilation system of a building. A building should be ventilated to provide the building with fresh air in order to satisfy human needs for an indoor climate with a good hygiene and good comfort. When designing the ventilation system of a building, the indoor air is primarily removed from rooms producing moisture and pollution from indoor activities, including rooms such as kitchens, utility rooms, bathrooms etc. Outdoor air is supplied to living rooms, bedrooms and similar rooms. The ventilation should not cause air velocities that locally exceed 0.15 m/s, which is normally considered to be the limit at which humans feel a draft from the airflow.

3 AIR PERMEABILITY MEASUREMENTS

In Denmark air permeability is measured by using the method described in DS/EN 13829 and ISO 9972:2006. For measuring the air permeability in large buildings, the building can be divided into smaller sections. One method for measuring the air permeability of a building is the so called Blower Door Test which is the test commonly used in Denmark.

Air permeability of a building is defined as the volume of air that has to be supplied to the building to maintain a constant difference in air pressure of 50 Pa between the interior and exterior of the building, across the building envelope. The air permeability has to be lower than 1.5 l/s per heated occupied m^2 of the building, measured as the mean of the infiltration and the exfiltration for a negative and a positive interior pressure, respectively. An air pressure difference of 50 Pa corresponds to the wind pressure generated by a wind speed of 10 to 12 m/s.

Wind flowing around a building will create an effective positive pressure on the exterior of the windward side and an effective negative pressure on the leeward side. At the windward side, air will seep in through leakages and be sucked out at the leeward side. Where the space in the building is compartmentalised, infiltration will create an effective positive pressure on the interior of the windward side and exfiltration will create an effective negative pressure on the interior of the leeward side, see Figure 2. If e.g. the doors between internal rooms are open, the overall internal space has the same pressure due to internal airflow; hence if the doors are closed, pressures in the rooms will depend on the airflow balance between the rooms. Before carrying out the Blower Door Test, it has to be ascertained that the weather conditions generate a pressure difference lower than 5 Pa between the interior and the exterior of the building. An air pressure difference of 5 Pa corresponds to a wind speed of approximately 6 m/s.

To comply with the Blower Door Test requirements, an airtight shell can be established by means of a building envelope consisting of building components and joints that meet the requirements for air permeability equal to or less than 0.00005 $l/(m^2\ s\ Pa)$.

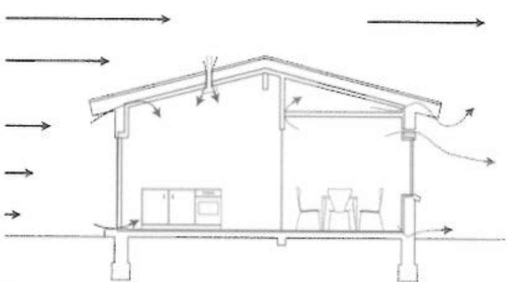

Figure 2. Wind flowing around a building will create an effective positive pressure on the exterior of the windward side and an effective negative pressure on the leeward side. At the windward side, air will seep in through leakages and be sucked out at the leeward side.

4 EXAMPLES OF PERFORMANCE

4.1 *Passage to the loft through the ceiling*

Figure 3 shows a hatch for passage to a loft through a ceiling. Where the airtight shell was located within the ceiling, a hatch was mounted in the ceiling and was built into the airtight shell. The hatch itself was airtight and the airtight shell of the hatch was extended to the airtight shell of the entire ceiling. By using a polyethylene foil for the airtight shell in the ceiling, the foil had to be securely attached to the frame of the hatch. A gasket between the opening part of the hatch and the frame of the hatch ensured that the hatch was airtight when it was closed.

Air penetration through the airtight shell can easily be located by creating a pressure difference between the interior and the exterior of the building. By maintaining a pressure difference, air penetration through unforeseen leakages can be revealed when designed openings in the building envelope are closed. Having a lower outside temperature compared with the temperature inside the building, infiltration can easily be revealed by maintaining a negative pressure inside and using thermograph equipment.

Thermograph equipment was used to show surface temperatures of an ordinary single-family house. Low surface temperatures inside the building, at normal indoor air temperatures, revealed thermal bridges or locations of infiltration, where cold air was sucked in because of a constant negative pressure created inside. An infrared thermographic observation of the ceiling with a hatch is shown in Figure 3. The colours of the infrared thermographic picture visualise the temperature of the ceiling. The upper picture shows an ordinary photo of the ceiling with the thermographic picture inserted at the lower right corner. The lower figure shows in detail how the airtight shell of the hatch should have been extended correctly to the airtight shell of the entire ceiling when fixed. The airtight shell in the ceiling was established by a polyethylene foil that also served as a vapour barrier. The polyethylene foil was placed between the wood trusses and the laths. In practice the polyethylene foil should have been mounted on the frame of the hatch and joint.

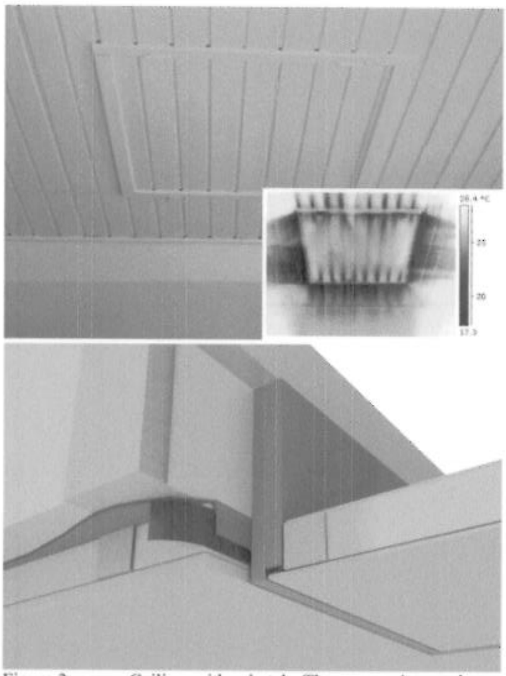

Figure 3. Ceiling with a hatch. The upper picture shows an ordinary photo of a ceiling with a thermographic picture inserted at the lower right corner. The thermographic picture shows the infrared thermographic observation of the ceiling with the hatch. The colours on the infrared thermographic picture visualise the indoor surface temperature of the ceiling. The lower figure shows in detail, how the airtight shell of the hatch has to be extended correctly to the airtight shell of the entire ceiling in order to keep the airtight shell intact. The airtight shell in the ceiling was established by a polyethylene foil that also served as a vapour barrier.

4.2 *Windows in lightweight constructions*

Figure 4 shows a window mounted in a wood-stud construction with the ceiling built parallel to the roof and the exterior wall serving as the building envelope. As for the ceiling, where the airtight shell was located within the ceiling, a window was mounted in the ceiling and thus built into the airtight shell. The window itself was airtight and the airtight shell of the window was extended to the airtight shell of the entire ceiling. By using a polyethylene foil as the airtight shell in the ceiling, the foil had to be securely attached to the frame of the window. A gasket between the opening part of the window and the frame of the window ensured that the window was airtight when it was closed.

Figure 4. Building envelope with a window. The upper picture shows an ordinary photo of a ceiling with two windows with a thermographic picture inserted at the upper left corner. The thermographic picture shows the infrared thermographic observation of the ceiling with the two windows The colours on the infrared thermographic picture visualise the interior surface temperatures of the ceiling. The lower figure shows in detail, how the airtight shell of the window should have been extended correctly to the airtight shell of the entire building envelope. The airtight shell in the wall and in the ceiling was established by a polyethylene foil that also served as a vapour barrier.

Discontinuities in the airtight shell can be located by using thermographic equipment when a constant negative pressure is created inside an ordinary single-family house. Low surface temperatures revealing thermal bridges or locations of infiltration where identified by using infrared thermographic observation of the ceiling with two windows, see Figure 4. The upper picture shows an ordinary photo of the ceiling with the thermographic picture inserted at the upper left corner. The lower figure shows in detail how the airtight shell of the window should have been extended correctly to the airtight shell of the entire building envelope, when built as a wood-stud construction. The airtight shell in the wood-stud construction was established by a polyethylene foil that also served as a vapour barrier. The polyethylene foil was placed within the insulation layer, in the ceiling between the wood trusses and the laths and in the exterior wall between the laths and the wood studs. In practice the polyethylene foil should have been mounted on the frame of the window and joint.

4.3 *Vent for ventilation mounted in the ceiling*

Figure 5 shows a vent for ventilation mounted correctly in the ceiling. The airtight shell was located in the ceiling and the vent was built into the airtight shell. The vent was fixed to a wood support attached to the wood trusses. The vent itself was airtight and attached in an airtight way to the airtight shell of the entire ceiling. The airtight shell of the ceiling was established by a polyethylene foil that also served as a vapour barrier. The polyethylene foil was placed between the wood trusses and the laths. The polyethylene foil was mounted on the frame of the vent and joint.

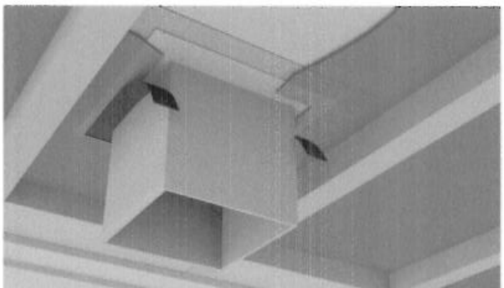

Figure 5. Ceiling-mounted vent for ventilation. The figure shows in detail how the airtight shell of the entire ceiling was attached to the vent. The airtight shell in the ceiling was established by a polyethylene foil that also served as a vapour barrier. The polyethylene foil was placed between the wood trusses and the laths. The polyethylene foil was joined to the frame of the vent.

4.4 *Conduits*

Figure 6 shows a properly designed conduit for a wire going through the ceiling. The airtight shell was situated in the ceiling and the conduit was built into the shell. The conduit was joined to the shell. The conduit itself was airtight and sealed to the airtight shell of the entire ceiling as well as to the wire. The airtight shell of the ceiling was established by a polyethylene foil that also served as a vapour barrier. The polyethylene foil was placed between the wood trusses and the laths. The frame of the conduit was mounted onto the polyethylene foil and joint. Similar conduits were established in the building envelope where the airtight shell was established by a polyethylene foil that also served as a vapour barrier or the radon barrier.

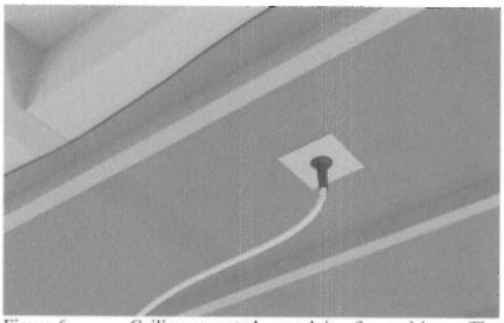

Figure 6. Ceiling-mounted conduit for wiring. The airtight shell of the entire ceiling was attached to the conduit. The airtight shell in the ceiling was established by a polyethylene foil that also served as a vapour barrier. The polyethylene foil was placed between the wood trusses and the laths. The frame of the conduit was joined to the polyethylene foil.

Heavyweight building components are considered to be airtight in themselves as well as able to seal if they meet the requirements for air permeability and those suitable for use in and as the airtight shell. Normally heavyweight building components, used as the load bearing inner wall of the exterior wall are considered to be airtight and able to seal if they have an overall homogenous density higher than 1600 kg/m3 and is equal to or thicker than 100 mm. For other heavyweight building components the airtight shell must be established e.g. by a layer of plaster.

Figure 7 shows a properly designed conduit for wires going through a heavyweight building component used as the load-bearing inner wall of the exterior wall. The airtight shell was established by a layer of plaster. The airtight shell located at the interior side of the exterior wall was covering the conduit or joined to a stopper, if not airtight in itself. Wires are fixed and kept in position in the conduit by the stopper. The stopper that fills out the remaining area of the conduit was joined to, or covered by, the shell itself. The stopper in itself was airtight and sealed to the airtight shell of the entire wall as well as to the wires. The airtight shell of the wall was established by a layer of plaster that also served as a vapour barrier. Similar conduits were established in the building envelope, where the airtight shell was established by a layer of plaster that also served as a vapour barrier or the radon barrier e.g. at the concrete floor slab.

For additional guidance and advice on designing and establishing an airtight shell that encases the heated interior of a building, see Valdbjørn Rasmussen and Nicolajsen (2007).

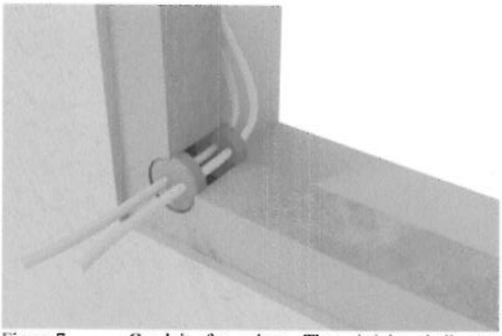

Figure 7. Conduit for wires. The airtight shell was established by a layer of plaster. The airtight shell was located at the interior side of the exterior wall. Wires were fixed and kept in position in the conduit by a stopper. The stopper fills out the remaining area of the conduit. The conduit itself was airtight and sealed to the airtight shell of the entire wall as well as to the wires. Wires were airtight in themselves. The airtight shell of the wall was established by a layer of plaster that also served as a vapour barrier.

5 DISCUSSION

The tightened energy provisions incorporated in the new Danish Building Regulations (Danish Enterprise and Construction Authority 2008), caused by the action plan (Ministry of Transport 2005), are intended to result in an energy reduction of 20 to 30% for new buildings compared with buildings built in accordance with the former Building Regulations. By focusing on the airtightening of the building envelope, heat loss from air penetration in buildings is to a higher extent controlled by reducing energy consumption for heating and comfort. This study focused on methods for designing an airtight shell that encases the heated interior of a building.

Air penetration through unforeseen leakages in the building envelope causes unnecessary heat loss and a risk of mould growth. The water vapour content in the outdoor air is low in winter. When the cold air enters the heated rooms indoors, it will be heated up and the relative humidity of the indoor air will decrease as a consequence (Andersen et al. 1993). The indoor air will be altered by water vapour generated by occupants, plants and everyday activities such as cooking and washing. In this case the air in a heated occupied room will contain higher vapour pressure than the outdoor air. In winter, air that leaks out through unforeseen leakages in the building envelope will decrease in temperature and rise in relative humidity. With exfiltration, the air is likely to condense within the insulation, thus increasing the moisture content and increasing the risk of mould growth as well as increasing the risk for decomposition of the building. By building airtight buildings, and ventilating them well by means of controlled vents, moisture and polluted air can be removed from the indoor environment in a proper way. A certain amount of air change is necessary to keep the relative humidity of the indoor air at an acceptably low level.

Air penetration through unforeseen leakages in the building envelope can easily be prevented. An airtight shell that encases the heated interior of a building should be introduced at the design phase. Typically the shell follows the building envelope, which consists of lightweight or heavyweight building components. Often lightweight wood-stud walls or heavyweight concrete wall elements are used mounted with windows, doors, ceilings, and roof and floor-slab constructions. This means that skylights, conduits, doors and windows become integral parts of the air-barrier system. Critical locations in the shell are situated, where building components are placed in staggered levels in between building components and at conduits, where installations are brought into the building.

For some building components the airtight shell can with advantage be established by a polyethylene foil that also serves as the vapour barrier placed within the building envelope. For the foil serving as a vapour barrier, it is crucial that the foil is placed in the insulation layer located at the warm side of the dew point in order to avoid condensation. For the airtight shell, it is important that the joints between building components are securely fixed. Furthermore it is crucial that the joints maintain their airtight properties during the lifetime of the construction and are not damaged or decompose during their service life. This entails a great deal of focus on how to establish the airtight shell on site as well as during the design phase.

6 CONCLUSION

Airtightness of building envelopes is a key factor in determining air permeability, heat loss, indoor air quality, maintainability and moisture balance within the building envelope and indoors. Air leakages through the building envelope contribute to the cost of ventilation, heating and cooling and also to moisture migration. Furthermore, airtightness is the most important property of building envelopes to understanding ventilation. Airtightness is important from a variety of perspectives mostly from movement of air through leaks, cracks, or other and unforeseen openings in the building envelope. Air penetration through unforeseen leakages often plays a decisive role in the moisture transport in a building, and ultimately the moisture balance in the building envelope. This affects the durability of the construction, leading to potential material emissions and a risk of surface mould growth, which in turn leads to a poorer indoor environment.

There is a direct connection between an airtight building envelope and low energy consumption for heating and comfort in the building. Air movements through the building envelope affect the indoor thermal comfort, ventilation and ultimately the indoor climate. These air movements cause heat losses directly by their influence on ventilation and by their effect on the function of the thermal insulation. With regard to a better heat-insulated building envelope, the importance of an airtight building envelope becomes even more pronounced in relation to the total energy consumption of the building. If a heat exchanger for the ventilation system of the building is used to ensure fresh air to satisfy human needs for hygiene and comfort, a less efficient system is provided, decreasing in efficiency with less efficient airtightness of the building envelope. Energy consumption is hereby indirectly affected and this influences the building's environmental impact.

Estimating that leakages in the building envelope increase the energy consumption by 20 to 30%, air-tightening of the building envelope becomes of even higher national importance and an instrument for complying with the Kyoto Protocol, United Nations (1998). However, a stronger national benefit requires implementation of airtight building envelopes in existing buildings.

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