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Interior insulation retrofit of a historical brick wall using vacuum insulation panels: Hygrothermal numerical simulations and laboratory investigations

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ABSTRACT

Old listed buildings need to be retrofitted to reduce the energy use for heating. The possible thickness of the insulation layer is limited by the existing construction. Vacuum insulation panels (VIPs) require less thickness than conventional insulation materials to reach the same thermal resistance. Therefore, it could be more appropriate to use VIPs than conventional insulation materials when retrofitting the building envelope of listed buildings. The aim of this study is to investigate the hygrothermal performance of a brick wall with wooden beam ends after it was insulated on the interior with VIPs. One- and two-dimensional hygrothermal numerical simulations were used to design a laboratory study in a large-scale building envelope climate simulator. The wall was exposed to driving rain on the exterior surface and a temperature gradient. The relative humidity in the wall increased substantially when exposed to driving rain. The moisture content in the wooden beams also increased. There was no significant difference between the relative humidity in the wooden beam ends for the cases with and without VIPs. However, it was found that the reduced temperature in the brick after the VIPs were added led to a higher relative humidity in the wooden beams. It was also clear that when VIPs were added to the interior, the drying capacity to that side of the wall was substantially reduced. Finally, calculations of the *U*-value showed a large potential to reduce the energy use using VIPs on the interior of brick walls.

1. Introduction

In Europe, the majority of the future building stock has already been built. The turnover in the building stock is low since the existing buildings fulfill a large part of the future housing demands. However, the increasing pressure to reduce the CO_2 emissions and energy use in the society urge for energy efficiency measures in the existing building stock [1]. Therefore, one of the main challenges in the building sector is to find ways to reduce the energy use for heating of the existing buildings. This can be achieved by a number of measures, such as heat recovery of the ventilation air or by adding thermal insulation in the building envelope [2]. In Sweden and Norway, especially the exterior walls of old buildings, from the late 1800s to early 1900s, have a low thermal resistance compared to current standards and requirements. In Swedish buildings built before 1960, the average *U*-value of the walls is 0.58 W/(m^2 K) [3] while it is 0.9 W/(m^2 K) for at least 100,000 Norwegian buildings from before 1945 [4]. These values should be compared to the general target *U*-value for retrofitted walls which is 0.18 W/(m^2 K) in Sweden [5] and 0.22 W/(m^2 K) in Norway [6]. Examples of buildings with brick walls that have been energy retrofitted have been presented by e.g. Morelli et al. [7], Weller et al. [8] and Häupl et al. [9]. As for Sweden, an overview of four listed retrofitted buildings from the 1940s to 1960s in Gothenburg was presented by Johansson [10]. All the buildings in that study had a brick façade and brick or aerated concrete walls. The retrofitting measures involved adding 30–50 mm glass wool on the exterior of the walls, protected by either a layer of render or a ventilated façade board. The calculated *U*-value was reduced from 0.83–1.73 W/(m^2 K) to 0.13–0.5 W/(m^2 K) after the retrofitting, depending on the existing construction and which measure that was used. Capener et al. [11]

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also studied a brick building in Gothenburg which was retrofitted with an External Thermal Insulation Composite System (ETICS) involving 50 mm glass wool and two layers of external render. Measurements showed a 27% reduction in energy use for heating and domestic hot water, and reduced moisture content in the wall. Another approach was proposed by Rasmussen [12] where 95 mm glass wool was added on the interior of a listed brick façade and 195 mm glass wool covered by render was added on the exterior of the remaining façades of a building from year 1900 in Copenhagen, Denmark.

Retrofitting of an exterior wall changes the hygrothermal performance of the wall. If it is not properly done, this could lead to damages and in worst case building failure [13]. When adding insulation to the exterior, the existing structure is kept in a warm and dry condition which is beneficial from a moisture point of view. However, the exterior wall surface becomes colder and more susceptible for moisture damages and organic growth. For example the previously mentioned ETICS, common in both new and renovated buildings in Europe, may have serious problems of biological growth causing deterioration and degradation of the exterior cladding [14]. In old brick masonry buildings the unprotected brick walls may have freeze-thaw damages. The addition of interior insulation can, in some cases, initiate freeze-thaw damage [15].

Many old buildings, in particular brick buildings, are considered to be of great historical value and are listed for their exterior appearance. The former Lyckholms brewery in Gothenburg, built in the late 1880s, is listed for its characteristic exterior expression [16], see Fig. 1. Therefore, exterior insulation is not permitted. In fact, it is estimated that 41% of the existing buildings in Sweden are unsuitable for exterior insulation of the façade. In 31% of the existing buildings exterior insulation is permitted, while it is dubious whether it is appropriate in the remaining 28% [17]. The situation in Norway is considered to be somewhat similar with many brick buildings unsuitable for exterior insulation. Hence, the only adequate solution to retrofit the walls of these buildings is to add interior insulation. This is a topic which has been investigated continuously during the years. Straube et al. [18] studied a number of brick buildings in the United States where interior insulation had been added and concluded that rain and water leakage issues have to be addressed properly and that there was a risk that wooden beam ends in the walls were damaged by the changed hygrothermal conditions in the wall. Also Künzel [13] showed that exterior walls insulated on the interior need to be combined with rain protection measures to avoid moisture induced damages.

When retrofitting old buildings, the prerequisites are given by the existing construction. The intermediate floors in old brick buildings are often carried by wooden beams which are embedded in the brick, see Fig. 1. Mold and dry rot can damage the wooden beams and the risk for that is higher when interior insulation is added because of the higher relative humidity in the wall. Inside the wall, there could be air leakage paths from the interior into the area around the wooden beam ends which can transport moist air from the interior. This will raise the moisture content even higher [19]. Also, driving rain could contribute to further raising of the moisture content in the wall and wooden beam ends, increasing the risk for moisture damages. Van den Brande et al. [20] studied the effect by rain water runoff on the water absorption of a façade. Depending on the type of material in the exterior of the façade, the additional water absorption by runoff varies. It was found that the effect was small for materials with a large capillary transport potential, such as brick and mortar. For other materials, the water absorption could be heavily underestimated since the drying of the surface is delayed by the presence of a water film on the exterior surface. In some cases the water absorption was doubled when taking the runoff into account compared to the case with no runoff.

The movement of water through the brick and mortar has many important consequences in buildings and it has therefore been studied by a number of authors, e.g. Hall [21] and Brocken [22]. While the majority of these studies involved water suction experiments from a free water surface, large-scale experiments where water suction in brick walls is studied during a real or artificial rain load, such as presented by Abuku et al. [23] and Piaia et al. [24], are rare. To the best knowledge of the authors, similar studies for brick masonry, as presented in this work, are not available.

A challenge when retrofitting old buildings is that the additional thickness of the wall is limited by e.g. the allowed reduction of the internal floor area. Novel highly efficient thermal insulation materials such as vacuum insulation panels (VIPs) increase the thermal resistance of the wall compared to conventional insulation materials with the same thickness. The thermal resistance of a VIP is 5–10 times higher than for conventional insulation materials [25,26] leading to a reduced thickness in the same scale. Alternatively, a higher thermal resistance can be obtained with the same added thickness. Therefore it could be more appropriate to use VIPs than conventional insulation materials when retrofitting the building envelope of listed buildings. A laboratory study on timber frame walls retrofitted on the exterior with VIPs was presented by Sveipe et al. [27]. It was shown that a 30 mm thick layer of VIPs could be added to the exterior without risk of causing moisture condensation in the wall, as long as the difference between the interior and exterior vapor content, i.e. the indoor moisture supply, was below 6 g/m^3. This is well above the average measured indoor moisture


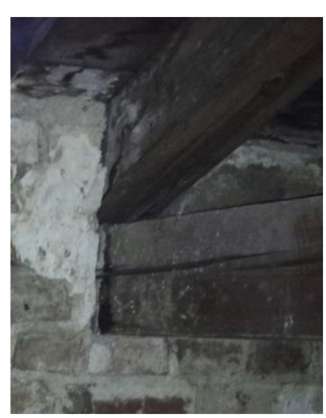

Fig. 1. Left: Lyckholms brewery in Gothenburg built in the late 1880s is listed for its characteristic exterior expression, which excludes exterior insulation as an option. Right: Connection of a wooden beam in a brick wall.