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# POSSIBILITIES OF IMPROVING THE THERMAL PROTECTION OF RESIDENTIAL BUILDINGS BY THE APPLICATION OF OVER-RAFTER ROOF INSULATION SYSTEMS

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**Abstract:** The need to save energy, as well as the constant tightening of regulations regarding thermal protection of buildings force the need to look for solutions increasing the thermal performance of building envelopes. One of the important issues in this regard is the appropriate thermal insulation of usable attics. Currently, two layers of mineral wool are most often used - one between the rafters and the other under the rafters. Recently, an alternative solution has emerged, namely PIR (polyisocyanurate) foam over-rafter roof insulation systems. The aim of the article is to assess the legitimacy of using this new method of roof slope insulation. Appropriate conclusions were formulated on the basis of the technical and economic analysis of PIR foam parameters and other insulation materials, and a case study in which one of the actual implementations of the over-rafter insulation was analyzed. It was found that the use of PIR panels as the external insulation of roof slopes gives benefits primarily in terms of improving the quality of thermal insulation works. The over-rafter system is easier to implement than the classical solution (fewer possibilities of assembly errors), and above all, it minimizes thermal bridges. In addition, PIR has a better thermal conductivity than mineral wool, which reduces the necessary insulation thickness, and the possibility of condensation inside the envelope and cold air infiltration is also limited. The barrier to the use of this solution is currently primarily the high price of PIR roof panels, but as shown, the benefits associated with improving the quality of insulation are taken into account and encourage investors to choose such a solution.
**Keywords:** energy-efficient building, quality of construction works, PIR roof panels, thermal insulation of roofs.

## 1. INTRODUCTION

The dynamic development of new technologies and the growing requirements of building users force a continuous increase in the quality of materials and construction works. Therefore, standards in the construction sector are constantly changing - old technologies are gradually eliminated, therefore companies that want to maintain the appropriate quality of their products and services must constantly monitor the development of new technologies (Rosak-Szyrocka and Janik, 2017; Siwiec and

Pacana, 2021). The energy quality of buildings is also constantly increasing. This is mainly due to the general need to save energy in connection with the need to counteract air pollution and adverse climate changes (Lis A. and Lis P., 2018). There is an increase in social awareness in this regard (Ingaldi and Dziuba, 2018). One of the administrative activities related to sustainable development in construction is the continuous tightening of regulations related to the thermal protection of buildings. In fact, an energy-efficient and passive house should now be the standard when designing buildings. The energy efficiency of a house is influenced by many factors (Szafranko, 2020). One of the most important of them is good thermal insulation of external envelopes, including the elimination of the so-called "thermal bridges". While the ETICS (External Thermal Insulation Composite Systems), which have been used for many years, have allowed for the effective elimination of this phenomenon in the case of insulation of external walls, the insulation of pitched roofs over residential attics causes problems related primarily to the need to carefully perform between-rafter insulation with the use of mineral wool boards. These shortcomings can be avoided by applying the recently used solution - over-rafter insulation with polyisocyanurate (PIR) foam panels. PIR foam is an improved version of the polyurethane (PUR) foam that has been used for a long time.

The aim of the article is to assess the legitimacy of using this new method of roof slope insulation.

## 2. METHODOLOGY OF RESEARCH

The presented analysis concerns the comparison of technical and economic parameters of over-rafter insulation with the classic methods of insulating utility attics, mainly with the use of mineral wool. The parameters of thermal insulation, the possibility of dampness in the insulation, resistance to fire, technological and functional aspects as well as the cost of works were analyzed. The analysis was made on the basis of literature, technical guides and own many years of professional experience. Above all, however, a case study was carried out on one of the actual realizations of roof insulation on a reconstructed single-family building. A site inspection was made and a targeted interview with the investor was conducted.

## 3. INSULATION OF THE ATTICS - HISTORICAL NOTE

Until the 1970s, residential attics were rarely used in individual single-family housing in Poland, mainly due to the lack of effective methods of insulating roof slopes. Leaking roofing was also a problem. In traditional (formerly wooden, later masonry) buildings in rural areas, the attic most often played the role of a hay or straw storage - this material also provided thermal insulation for living quarters, but it was also the cause of many fires. In buildings not related to farms, full flat roofs (poorly insulated) or unused attics were built. In urban development, poorly insulated attic rooms were often a synonym of poverty.

Since the 1980s, along with the popularization of mineral wool boards, as well as vapor barrier films and windproofing membranes (roof membranes), it was already possible to sufficiently insulate roofs. During this period, insulation was applied between the rafters (oblique part of the partition) and between the collar beams (horizontal ceiling) with 5÷10 cm thick mineral wool boards. The horizontal ceiling based on collar beams divides the attic into the lower usable part and the upper non-usable part. The mineral wool produced then was of much lower quality than today - the boards were very soft and had high water absorption. Currently, hydrophobized boards are mainly used, which significantly improves their quality.

The successively raised requirements for thermal protection forced an increase in the thickness of the insulation. At the beginning of the 20th century, the standard was already 20 cm thick (usually two 10 cm boards). As the standard rafters have dimensions of 14÷16 cm, wooden battens nailed under the rafters were used - in this way the required insulation thickness was obtained. Similarly, the space between the collar beams was insulated, which was covered with e.g. boarding (Fig. 1a). The rafters and collar beams were therefore not insulated and formed a thermal bridge (Fig. 1b).

In recent years, in order to meet the current requirements, the insulation thickness of approx. 25 cm is most often used. The insulation is laid in two layers: between the rafters and under the rafters on a metal or wooden frame (battens perpendicular to the rafters). This method of installation has limited thermal bridges, as the rafters are also insulated in this way. It does not change the fact that proper mineral wool insulation requires great care. In practice, many assembly errors are encountered, above all:

- mineral wool boards (or mats) are "compressed" during assembly, the effective thickness of the insulation is reduced and its thermal parameters deteriorate,
- the boards are pressed against the wind barrier without a ventilation gap; such action is allowed only if a membrane with high vapor permeability is used, otherwise the mineral wool in the structure cannot dry naturally,
- careless assembly results in leaks between adjacent boards or between the boards and the structure, which generates additional thermal bridges,
- leaks in the roof covering or a poorly laid roof membrane results in water penetration or condensation inside the insulation.

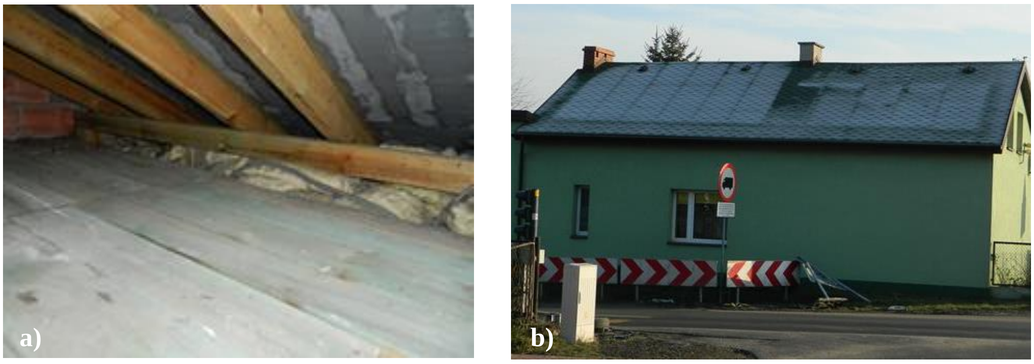


Fig. 1. Between-rafter insulation with mineral wool: a) view of the unused part of the attic; visible stains on the membrane after moisture, b) visible thermal bridges on the frosted roof (own photos)

It should be added that mineral wool now has better thermal insulation than, for example, 20-30 years ago. Manufacturers currently declare the thermal conductivity of $\lambda$ approx. 0.033÷0.04 W/(m·K), previously the calculated value was most often used at the level of 0.04 W/(m·K) or worse.

Styrofoam boards (polystyrene) for insulation of pitched roofs with wooden structure was practically not used in the case of between-rafter insulation. There are solutions using polystyrene shapes or boards for over-rafter insulation (Podwysocka, 2013), but these solutions are not popular. Styrofoam boards are commonly used in the insulation of flat roofs, when they are laid on a concrete substrate.

## 4. CHARACTERISTICS OF POLYURETHANE INSULATION

Polyurethane, in its classic version (PUR foam), has long been used in construction and other areas (sponges and foams used in the furniture, automotive, textile industries, etc.). So far, the best known in the construction industry are sandwich panels with coated sheet linings, as well as assembly foams and pipe covers. Sandwich panels are widely used as a light curtain wall as well as roofing for warehouse, industrial, etc. made of steel construction. However, PUR foam was rarely used to insulate masonry walls and classic roofs with wooden trusses - the $\lambda$-value for standard PUR is similar to that for mineral wool and polystyrene, so the use of polyurethane panels was not technically and economically justified (polyurethane panels require double-sided cladding).

In recent years, the production of an improved version of this material, namely PIR (polyisocyanurate) foam, has developed. Generally, it has better thermal insulation than PUR, but its insulation depends on the structure of the material and the method of application (Thermal insulation, 2006; Sipur, 2021).

There are two types of PIR foam structure:

- open-cells (less than 20% of closed cells),
- closed cells (over 90% of closed cells),

and two methods of application:

- by spraying, this method has been used for a long time, also for the application of classic PUR foam, mainly for renovation works,
- by installing the panels.

Open-cell insulations have worse insulation parameters - the $\lambda$-value is 0.035÷0.042 W/(m·K). They also have greater water absorption and lower resistance to aging (Berardi, 2019). Their advantage, however, is higher vapor permeability, so they are used where this parameter is crucial, e.g. when renovating and insulating existing roofs. These insulations are mainly applied by spraying.

Closed-cell PIR foam can be applied both by spraying (Gravit et all., 2017) and in the form of panels. PIR boards have flexible claddings on both sides (cardboard laminated with aluminum foil, fiberglass, bituminous materials). These claddings can be divided into gas-tight and non-gas-tight. Manufacturers most often declare the thermal conductivity $\lambda$:

- 0.026÷0.028 W/(m·K), for spraying,
- 0.025÷0.027 W/(m·K), for panels with non-gas-tight claddings,
- 0.020÷0.025 W/(m·K), for panels with gas-tight claddings.

The latter values are currently the best value of any material commonly used in construction (Sipur, 2021). The conducted research shows that the thermal conductivity of PIR foam is sufficiently stable at low temperatures, increasing noticeably at a temperature 70°C (Macaveckas et all., 2021).

## 5. ANALYSIS OF TECHNICAL AND ECONOMIC PARAMETERS

The panels for over-rafter insulation are made of closed-cell PIR with gas-tight cladding. As already mentioned, the great advantage of PIR is high thermal insulation. As calculated (without taking into account thermal bridges and insulation properties of the remaining layers of the roof slope, which is of no great importance here), in order to meet the current Polish requirements regarding thermal transmittance through the roof slopes ($U \leq 0.15$ W/($m^2$·K), we need:

- approx. 15 cm of PIR foam with $\lambda$ = 0.023 W/(m·K),
- approx. 20 cm of material with $\lambda$ = 0.031 W/(m·K),
- approx. 23 cm of material with $\lambda$ = 0.035 W/(m·K),
- approx. 25 cm of material with $\lambda$ = 0.038 W/(m·K),

The difference in the required thickness of the insulation is therefore significant. This translates into less load on the roof elements. PIR producers declare a density of 30÷36 kg/m$^3$, which is comparable to the weight of mineral wool mats, mineral wool boards have a higher density, even over 100 kg/m$^3$.

The water absorption of PIR panels does not exceed 2%, which is lower than that of polystyrene (up to approx. 5%) and much lower than mineral wool mats.

Water vapor permeability, similar to polystyrene, is low, unlike mineral wool. This is a drawback because too high tightness of building envelopes combined with ineffective ventilation may cause moisture on the inside.

PIR plates have a high air flow resistance. This reduces the risk of unfavorable cold air infiltration into the structure, which is often found in the case of mineral wool.

PIR panels have one of the best insulation materials with a compressive strength (compressive stress at 10% relative deformation) of at least 150÷500 kPa, which is comparable to hard foamed polystyrene (manufacturers of classic EPS usually declare 80÷100 kPa) and of course much better than mineral wool boards for roof insulation.

As for the reaction to fire, PIR foam, similarly to polystyrene, is classified as "not spreading fire" and "self-extinguishing", so in this respect it is inferior to mineral wool classified as "non-combustible" material. This may constitute a certain limitation in the use, for example in the case of a plot situated at the border, there is a need to use the so-called firewall (the part of the wall protruding above the roof). The fire resistance of PIR can be improved by using appropriate chemical additives, e.g. graphite (Modesti and Lorenzetti, 2003; Kurańska et all., 2015; Lenz et all., 2020).

PIR foam waste is difficult to recycle. Research is conducted on this topic, e.g. the possibility of chemical recycling (Modesti et all., 2018) or the use of this waste for the production of lightweight concrete blocks (Kanchanapiya et all., 2018).

Comparing the cost of different insulation materials is not easy. Manufacturers offer a wide range and various technical parameters in the context of various places of application. Table 1 provides an analysis of the prices of materials for PIR over-rafter panels, mineral wool boards for the insulation of pitched roofs and polystyrene panels used mainly for wall insulation (made of classic EPS and graphite polystyrene). The prices apply to 15 cm thick panels and are the average prices of offers from several producers of them with the same $\lambda$-value. In order to take into account the different thermal conductivity of the materials, the product of the price and the $\lambda$-value was used as an index.

Table 1
Cost analysis of exemplary variants of material 15 cm insulation panels

| **Parameter** | **PIR** | **Mineral wool** | **EPS polystyrene** | **Graphite polystyrene** |
|---|---|---|---|---|
| Unit price p [PLN/m$^2$] | 115 | 25 | 40 | 46 |
| $\lambda$-value [W/(m·K)] | 0.023 | 0.035 | 0.038 | 0.031 |
| Index: p $\times$ $\lambda$ | 2.65 | 0.875 | 1.52 | 1.43 |

Source: (own analysis)

The data presented in Table 1 does not look good for PIR. It is by far the most expensive material, even taking into account its better thermal insulation. Undoubtedly, this is a significant limitation, especially in the case of investments carried out under the public procurement procedure, where the price is most often of key importance.

## 6. ANALYSIS OF INSULATION TECHNOLOGY - CASE STUDY

The analysis of the technology of over-rafter insulation was made on the example of a usable attic superstructure in a single-family building located near Czestochowa. A site inspection was carried out and an interview with the owner was conducted, who also presented and made available photographic documentation from the construction period (Fig. 2-3).

The building with a development area of 105 $m^2$ was erected in the 1960s. Its architectural form was typical of rural construction from that period (Brycht and Respondek, 2018): a one-story brick house with an unused attic, a gable roof with an inclination angle of approximately 45°.

The scope of the superstructure made in 2020 included the demolition of the existing structure to the level of the ceiling above the ground floor. The new 24 cm thick gable walls and knee walls are made of porous ceramic hollow bricks. A classic wooden roof truss was used - rafters 7×14 cm with horizontal double collar beams, as well as purlins and wall purlins 16×16 cm.

Over-rafter insulation made of 15 cm PIR panels with aluminum foil cladding was used. The roof was covered with metal roofing tiles on a classic wooden frame (counterbattens and battens), a roof membrane was placed between the roofing and PIR panels.

External walls were insulated from the outside with the use of ETICS with 15 cm thick polystyrene. The inner walls of the lower, usable part of the attic are finished with gypsum plasterboards on a classic metal frame. The ceiling is also made of gypsum plasterboards hung to collar beams. The space between the collar beams was not insulated, OSB wood-like boards were attached above them, constituting the floor of the upper, unused part of the attic. Underfloor heating is used in the residential part. There are also light partition walls with mineral wool filling (Fig. 3-4).

The completed roof insulation consists of 60-120 cm boards screwed directly to the rafters with appropriately long system screws through the first counterbatten placed on the panels. The screws are screwed in at an angle of approx. 45 ° to minimize the risk of the panels tearing off due to wind suction. Cutting the panels is easy, and their joints are secured with a system aluminum tape. The laid panels are so durable that the transfer of assembly loads is not a problem. They can also be walked on (of course, with appropriate caution).

After laying the PIR panels, the roof membrane was laid and then the second counterbatten was attached. In this way, the roof membrane is ventilated on both sides, which is advantageous in terms of the rapid evaporation of moisture. Counterbattens and battens perpendicularly screwed to them are the substrate for the roofing (Fig. 2).

Fig. 2. Roof covering with steel tiles on a wooden frame (Investor's photo, 2020)

When asked why he chose this solution, the investor replied that it was for practical reasons. The over-rafter panels are expensive as a material, but the assembly technology is much simpler than using mineral wool. Part of the work is eliminated, first of all there is no need to board the roof slopes, which generates noticeable savings. An interview with contractors conducted by the investor prior to the start of construction showed that the cost of comprehensive execution of all works (including materials) in the case of mineral wool would be only 15÷20% higher than with the use of PIR panels (with a similar level of insulation of partitions).


Fig. 3. Pictures from the implementation stage: a) roof insulation, b) general view (Investor's photos, 2020)

The investor also took into account the significant simplification and acceleration of the works, as well as the risk that the more complicated technology of thermal insulation with mineral wool may lead to assembly errors, and in the future to the disclosure of defects that would be costly to eliminate, e.g. thermal bridges, water and vapor penetration inside the envelope, excessive cold air infiltration. Another positive aspect noticed by the investor was the fact that the insulation on the outside of the rafters did not reduce the internal volume of the attic.

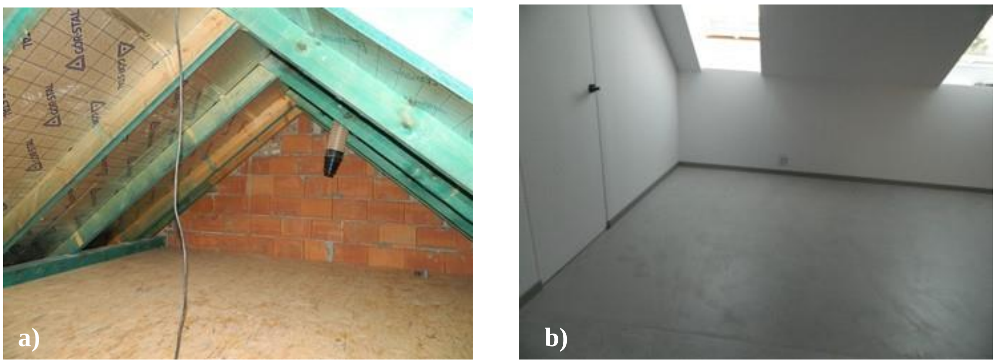


Fig. 4. Pictures after the implementation: a) upper part of the attic, b) lower part of the attic (own photos)

The investor, when asked how he found out about such a technology, replied that he works in the construction industry and knows new solutions, besides, he is a man open to such solutions. He also stated that after the first winter he did not notice any faults and inconveniences and that the appropriate thermal comfort was maintained.

## 7. DISCUSSION OF THE RESULTS

In the case of classical mineral wool insulation, the insulating layers are placed between the rafters, most often only at the level of the usable part of the attic. Continuity of insulation is achieved by insulating the ceiling above the lower part of the attic. In this way, the upper part of the attic is not insulated. Although this is not a strict rule - simultaneous insulation is also used in the upper part of the rafters and in the ceiling. In the case of over-rafter panels, the insulation must be distributed over the entire surface of the roof, also on the eaves (which is not advantageous because insulation is not needed at this point). The upper part of the attic is therefore always insulated, which is advantageous especially in the summer, as this space is not exposed to overheating. The investor decided that there is no need to insulate the ceiling, which, according to the author, is a shortcoming. As a result, the heated volume increases, which is not needed. Additional insulation between collar beams, e.g. with a mineral wool mat, does not generate high costs, and the use of this solution would additionally reduce heat losses.

PIR boards are the complete opposite of mineral wool in terms of water vapor and air permeability. As already mentioned, high airtightness of the partitions is beneficial, but only on the condition of effective ventilation of the rooms, which was implemented by the investor.

Over-rafter insulation also gives better possibilities of correct (without thermal bridges) installation of skylight windows. In the case of between-rafter insulation, proper insulation of the joint between the window frame and the roof is more difficult. In the case of over-rafter insulation, however, the window frame is substantially in contact with the insulation, which is more advantageous.

Other materials can also be used to make over-rafter insulation: hard polystyrene or hard mineral wool boards on boarding, it is also possible to combine over-rafter and between-rafter insulation. However, PIR foam boards show here the best insulating properties combined with appropriate mechanical strength.

Of course, each recently used solution generates a certain risk related to the uncertainty of how PIR panels last in the long term on real structures (PU Europe, 2011).

## 8. CONCLUSION

The conducted analysis showed that the over-rafter insulation system of a pitched roof is better than the between-rafter system due to its simplicity and minimization of thermal bridges (there are only point thermal bridges in the places of the screws). The solution of using PIR foam panels presented here seems to be optimal from the point of view of maintaining the appropriate energy parameters of the building and the appropriate quality of construction works. PIR panels as a material are three times more expensive than mineral wool roof panels (even taking into account their better $\lambda$-value), but after taking into account the elimination or simplification of some works, the overall cost of roof insulation is only 15÷20% higher. An additional factor justifying the choice of this technology was, in the analyzed case, the reduction of the risk of assembly errors. Such errors often occur in the case of between-rafter insulation with the use of mineral wool and may, during operation of building, reduce the energy efficiency of the envelope and worsen the thermal comfort in the rooms.

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