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USE OF THERMOGRAPHY FOR DETERMINING PLACES IN DANGER OF THE MOLD GROWTH IN RESIDENTIAL BUILDINGS

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ABSTRACT: The mold present in buildings is a factor causing, among others, threat to the health of residents, degradation of building materials, destruction of wall surfaces and furniture adjacent to molded partitions. This article examines the usefulness of thermography to identify areas at risk of mold growth in homes. For this purpose, a thermal imaging camera was used to create thermograms of building partitions. The thermograms were processed to determine the possibility of mold appearance and the extent of its development. The presence of moisture on barrier surface is one of the preconditions for mold growth. Thermogram analyses were carried out using three methods for determining critical temperature below which moisture condensation occurs on the surface of the barrier. A method based on the surface temperature factor proved to be the most useful one to determine the extent of mold development f_{Rsi}. The usefulness of the thermovision method to determine the area of mold growth has been verified practically through visible traces of mycelium on the examined walls and ceilings. When analyzig thermograms, it is required to take many factors into account. Therefore, a person interpreting thermograms must have appropriate knowledge in the field of thermovision and building physics.

KEY WORDS: building physics, thermography, humidity, biological degradation, microclimate

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Introduction

The problem of biodegradation of materials from which a building is built has been known for a long time. It is caused, for instance, by bacteria, fungi and molds. Their spores are present in the air of practically every building. Moreover, the adequate thermal and humidity conditions, as well as a suitable substrate, will suffice for their development. They appear as a mildew bloom spoiling the aesthetics of rooms and destroying the attacked material. Mold also affects the health of people and animals inhabiting the attacked rooms of a building. Their mycotoxins are the cause of many diseases e.g. allergies, and can even cause cancer. The impact of such microorganisms on the health of people in the building is one of the factors of the so-called Sick Building Syndrome; SBS for short. As early as in the 1990s, WHO reported that SBS occurs in as many as 30% of new and modernized buildings (WHO, 1990).

Problems with increased humidity usually appear in buildings where windows have been replaced with new and airtight ones. The tenants of these buildings, due to ill-conceived thermal energy savings, do not ventilate the rooms during periods of increased moisture emissions, causing mold growth. Building regulations existing since 2008 (WT, 2013) have introduced the need to use more airtight windows. At the same time, in the case of natural ventilation, the necessity to use diffusers in windows, balcony doors or in external walls was emphasized. Unfortunately, it happens quite often that the ventilators are sealed during the winter because, in the minds of the residents, the rooms are much colder, resulting in increased heating bills.

Even periodically increased indoor air humidity can cause surface condensation and deep-water vapor condensation in the partition, which supports mold growth. The deposition of mold spores in such places initiates the development of mold colonies. Condensation is caused by lowering the surface temperature below the so-called dew point. A significant reduction in the temperature of the partition surface in a building takes place when constructional and technological mistakes were present in the design process. They may also occur at the stage of building completion.

With the help of thermovision, the presence of mold cannot be directly detected. It can be used to find damp places where mold may or has already been formed.

Causes and effects of fungi and mold appearance in the building

Mold spores can be found in many places, including house dust, contaminated building materials, and – in autumn in – the outdoor air. For their development, a temperature of approximately 18°C, air humidity exceeding 60% and a nutrient-rich substrate are sufficient (Charkowska, 2005; Gawin, 2007). Such conditions occur most often in closed, warm and humid spaces, such as attics, basements, closed underfloor spaces or poorly ventilated flats. In those cases, in the air with the moistened surface, a specific ecological niche that allows the growth of mold colonies is created (Wołejko, 2011; Gutarowska, 2010).

The increase in the humidity of the substrate – the surface of the partition – may take place as a result of leaks in the external partitions (roofing, wall cracks), moisture rising from the ground and condensation on the surface of a building partition (Hyun-Hwa Lee, et al., 2016).

Hot air with a relative humidity RH of approximately 80% and a temperature of 22°C contains enough water vapor to allow condensation of water vapor to start in contact with partition surface at the temperature of approximately 18°C. Such a temperature reduction of 4 degrees can take place in the winter on the surface of thermal bridges in the building (Sedlbauer, 2002; Ickiewicz, 2015-2017). These are places in the construction of partitions, where there is a discontinuity in the thermal insulation or in the material with a high thermal conductivity coefficient λ. In addition to thermal bridges, the temperature drops in sites where, with a combination of several external partitions, the outflow of heat from the outer surface occurs in two or three directions. This causes the cooling of the internal surface of such a connection, resulting in a drop in its temperature. Such sites, referred to as geometrical bridges, include – for example – building corners, connections roofs or roofs of unheated lofts with corners of the building, connecting the walls with the ceiling above the passage in the building. Covering these places with furniture or curtains creates a zone where humidity, due to weaker air circulation, can last for a long time (figure 1). Therefore, especially in the above-mentioned sites, mold infestation occurs (Hyun-Hwa Lee, et al., 2016; Gawin, 2007).

Other places where, under high indoor air humidity, water vapor condensation may occur, are the surfaces of cold water pipes in the sanitary installation and the surfaces of the ventilation risers (Wołejko, 2011). Wall surfaces of ventilation pipes can cool down due to the reverse air draft. This is particularly the case on the last floors of buildings, where gravitational ventilation is very poor. Then it is enough to turn on the exhaust fans in the bathroom or kitchen for a reverse sequence to be created through the remaining ventilation ducts.

The presence of fungi and mold in the building, in addition to the unpleasant musty smell, may be accompanied by symptoms, such as:

- layers of varying intensity and color on the surface of the partition,
- discoloration of building materials,
- decomposition of molded wallpaper or drywall,
- flaking paint coatings,
- softening the structure of wood and wood-based materials, e.g. fibreboards on the back of furniture,
- increase in soil moisture (some types of fungi can synthesize water from the air).

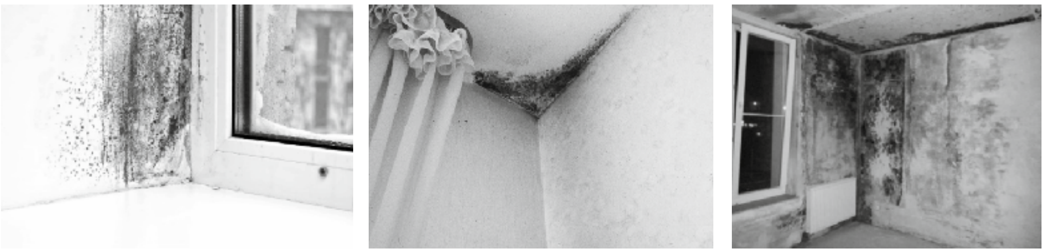

Figure 1. Examples of mold locations in apartments (window reveal, upper corner of the room, behind the curtains and furniture)

Source: author's own work.

In flats, the most common forms of mold present in the air are spores and parts of hyphae. The most common molds in this environment are fungi assigned to the classes *Deuteromycetes* and *Zygomycetes* (Gutarowska, 2010). These classes may include mold fungi, which are classified as inside home: *Aspergillus*, *Penicillium*, *Alternaria*, *Cladosporium*, *Mucor*. They are the main causes of allergies and other more serious diseases.

The growth of microorganisms, including molds and bacteria, contributes to the destruction of organic and inorganic materials used in construction. This process is complex and, as a consequence, there is a decline in the quality of materials, which in the literature is called "biodeterioration". This is related to the reduction of aesthetic and hygienic features and often deterioration of the mechanical properties of building materials (Charkowska et al., 2005). Organic materials attacked by fungi are mostly: wood, paper, wallpapers, paint coatings. The deterioration of these materials is caused by the exoenzymes produced by these microorganisms.

Inorganic materials on which molds can develop are: ceramics, plasters, concretes, stone materials, glass and even construction products from metal alloys. The molds developing on these materials give off the radicals of acids and other substances that cause the process of chemical destruction of materials. This interaction resembles a corrosive process and that is why it is called biological corrosion.

Research methodology

Thermography was used for studying the possibility of surface condensation and mold growth. With its help, areas on the surface of baffles where the temperature drops below critical levels, which, in turn, causes condensation (dew point) were determined.

The unquestionable advantages of the thermovision method are the non-destructive nature of tests and the speed of measurement. The thermal image camera registers the distribution of infrared radiation on the observed surface. The apparent temperatures corresponding to this distribution without any corrections are not an accurate representation of real temperatures.

To precisely determine the temperature of the tested surface using the thermovision method, it is necessary to take into account the influence of several factors. It is obligatory to enter the parameters of the object and the measurement environment (PN-EN 13187, 2001; Nowak, 2012; Walker, 2004; Więcek, 2011). The parameters are:

- air temperature (atmosphere),
- ambient temperature (reflected apparent temperature),
- object's emissivity Ɛ,
- distance between the object and the camera,
- relative humidity *RH*.

Thermovision tests conducted inside the building make it possible to reduce the impact of some of the above-mentioned factors. For example, the correction of attenuation of infrared radiation by the water vapor contained in the air is not so important due to the small distance between the camera and the object. In addition, in the case of external examinations, the influence of radiation temperature of the horizon and the half-space around the building should be additionally determined (Walker, 2004; Kruczek, 2015).

Equally important is the large difference in temperatures between the exterior and interior environment of the building, changes in air temperatures before and during testing, wind speed, solar radiation and no precipitation. The angle at which we observe the examined surface is also significant, because more than 50°, the emissivity of the surface ε is highly reduced (Nowak, 2012; Więcek, 2011). For this reason, the observations should be carried out preferably perpendicularly to the surface of the partitions.

Moisture detection on the surface of partitions is possible due to three factors. The first is the evaporation of water causing the cooling of the surface. The second effect of moisture is the increase in thermal conductivity of the moist material, resulting in a reduction in the surface temperature inside the building. The last consequence of moistening is the change of the thermal inertia of the material of the building envelope, which affects the slower "thermal response" of the material at a rapid change in air temperature in the room.

The first method used in the research was calculating the dew point, the temperature at which the moisture contained in the air reaches saturation and begins to condense. On the basis of thermovision measurements and hygrothermal conditions, areas with temperatures lower than the dew point temperature increased by 1°C were determined on the thermogram.

Assumptions for this method are similar to those in the PN-91/B-02020 standard (PN-91/B-02020, 1991). The dew point temperature is calculated according to formula:

$$\theta_s = \sqrt[8]{\frac{RH}{100}} \cdot (112 + 0{,}9 \cdot \theta_i) + 0{,}1 \cdot \theta_i - 112 \quad (1)$$

where:
RH – relative humidity of the internal air in %,
θ_i – air temperature in the room in °C.

The second method is about determining the temperature factor f_{Rsi} and the temperature of the internal surface of the building component at which condensation will occur, according to the calculation method included in PN-EN ISO 13788 (PN-EN ISO 13788, 2003). According to the standard, the risk of mold growth due to condensation on the inner surface of the partition can occur when in given external climate conditions the value of the temperature factor $f_{Rsi,min}$in the critical month will be greater than the value of f_{Rsi} factor for the partition. The temperature factor on the inner surface is calculated for the relative air humidity in the building of 80% – possible mold growth.

$$f_{Rsi,min} = \left(\theta_{si,min} - \theta_e\right)/(\theta_i - \theta_e) \quad (2)$$

where:
$\theta_{si,min}$ – the minimum allowable surface temperature determined for a given location dependent on the temperature and humidity of the outdoor air and the load class of the indoor humidity in the building in °C,
θ_e – outside air temperature in °C,
θ_i – internal air temperature in °C.

For the partition, the temperature factor on the internal surface f_{Rsi} is calculated from the formula below, having the computed value of the heat transfer coefficient U of the partition.

$$f_{Rsi} = \left(\frac{1}{U} - R_{si}\right)/\frac{1}{U} \qquad (3)$$

where:
U – heat transfer coefficient of the partition in W/(m^2·K),
R_{si} – resistance to the heat transfer on the inner surface for the walls equals 0,25 m^2·K/W.

With a thermovision camera, it is possible to determine from the thermograms, without calculating the heat transfer coefficient U, the critical temperature factor f_{Rsi} of the tested partition from the formula 4. For new buildings it can be assumed that the appropriate critical value for comparisons will be f_{CRsi}=0.75 (Walker, 2004). This coincides with the required temperature factors in Switzerland and the United Kingdom, for which f_{Rsi} is also 0.75. In Polish legislation (WT, 2013) it is allowed that when the indoor temperature in the room is at least 20°C, and the average monthly humidity RH = 50%, the limit value f_{CRsi} is 0.72. In Europe, the requirements for the critical value of the temperature factor to avoid mold growth are different. In Germany and Belgium, the minimum values for the maximum relative humidity RH = 80% are f_{Rsi} =0.70. In Finland, for new buildings, the required value for f_{Rsi} for floors is 0.97 and for external walls 0.87.

In order to check the condition for the temperature factor, three surface temperatures should be determined thermographically: within the thermal anomaly θ_{sia}, in a nearby area with good thermal insulation located on the inside θ_{si} and outside θ_{se} of the partition.

$$f_{Rsi} = (\theta_{sia} - \theta_{se})/(\theta_{si} - \theta_{se}) \qquad (4)$$

where:
θ_{sia} – temperature of the surface at the place of thermal anomaly, e.g. thermal bridge in °C,
θ_{se} – temperature of the external surface outside the anomaly, with good insulation and temperature factor $f_{Rsi,min}$ greater than the critical for a given location of the building in °C,
θ_{si} – temperature of the internal surface outside the anomaly, with good insulation and temperature factor $f_{Rsi,min}$greater than the critical for a given location of the building in °C.

By converting the above equation, we can determine critical temperature θ_{sia}, below which there will be a risk of moisture condensation and mold growth. For this purpose, an isotherm for the temperature θ_{sia} from the formula 6 should be set on the thermography. Below this temperature critical surface humidity will occur, creating the risk of condensation and mold growth. The limit value of f_{CRsi}recommended in the literature for thermal imaging tests (Walker, 2004) equals 0.75.

$$\theta_{sia} = f_{CRsi} \cdot (\theta_{si} - \theta_{se}) + \theta_{se} \quad (5)$$

where: symbol translation as above.

Results of thermovision inspections

The Flir T450sc and SC660 cameras were used for thermovision inspections. The thermal resolution on both cameras was not worse than 0.03°C (T450sc) and 0.045°C (SC660). The optical resolution of the obtained thermograms was 640x480 (T450sc in UltraMAX mode). The examination took place on February 18, 2016 and January 13, 2014, in both cases with the clouded sky and no precipitation.

In order to check the possibility of mold growth and for correct temperature indications on thermograms, during the measurements, the humidity of the air at the measurement site was recorded using Extech's electronic psychrometer MO297 cooperating with the cameras.

Both cameras used have a measurement mode, which in assumptions is consistent with the dew point. It enables the isotherm to be set below which the water vapor condenses on tested surface (RH=100%). During measurements using this mode, the parameters described in the paragraph 3 of the article, should be entered into the camera. On the screen of the camera, you can observe sites where condensation takes place.

The first test site where a risk of moisture condensation and mold formation may exist is the connection of a non-insulated cantilever balcony slab with an insulated external wall. Such a situation occurs quite often with "economical thermomodernization" and improper thermal insulation of a thermal bridge in the external wall with balconies or loggias. The author of this article encountered such a situation in 78 buildings in north-eastern Poland when making thermograms of buildings insulated with the ETICS (Ickiewicz, 2015-2017).

During local inspection, a building insulated with 15 cm polystyrene, made in the OWT-67N technology was tested. In the field of insulation works, the insulation of the balcony support plate was omitted (figure 2). The effect of the board not being warmed is visible on the thermograms (figures 3, 4 and 5).

Figure 2. Balcony with the uninsulated plate

Figure 3. Thermogram of uninsulated balcony plate with visible thermal bridge

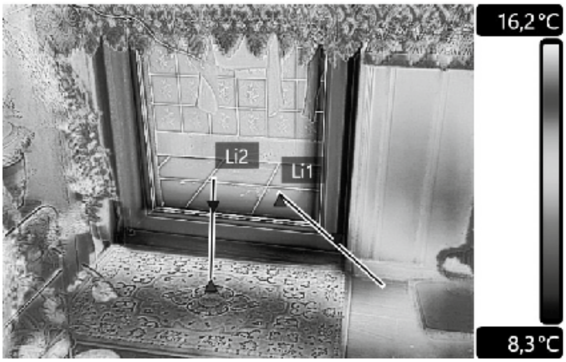

Figure 4. Thermogram of temperature distribution at the balcony door

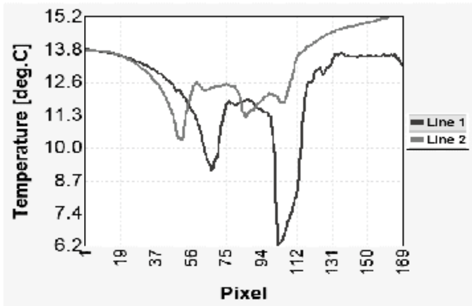

Figure 5. Temperature distribution in the profiles Li1 and Li2 at the threshold of the balcony door

Source: author's own work.

From the conditions for water vapor condensation in room temperature θ_i = 18.5°C and indoor air humidity *RH* = 62%, the dew point temperature was calculated as θ_s = 11°C. On the thermogram (figure 6), the surface with a dew point temperature increased by 1°C and below was marked with arrows. In this area, according to the assumption in the Regulation (PN-91/ B-02020, 1991), condensation of water vapor may occur. This method, however, has limitations, as the camera will indicate the place of condensation, with a one degree reserve, only in the current conditions of the external climate and the heat-humidity conditions prevailing inside the room.

After determining the temperature of the internal and external areas and the area of the thermal anomaly at the threshold of the balcony door, critical temperature for the factor f_{CRsi} = 0.75 was θ_{sia} = 9.9°C. On the thermogram

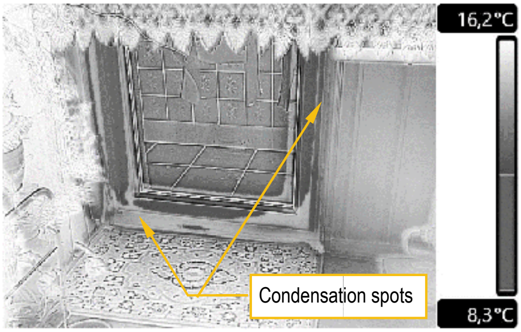

Figure 6. Thermogram of the surface condensation site at the balcony door – a condition for dew point θ_s

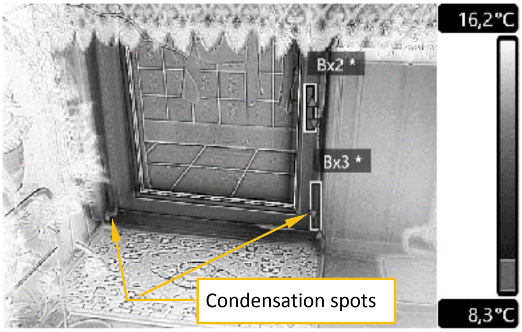

Figure 7. Thermogram of surface condensation site at the balcony door – a condition for critical temperature to prevent the growth of mold θ_{sia}

Source: author's own work.

(figure 7), an area with a temperature lower than 9.9°C was marked with arrows.In these places condensation and the development of mold may occur. Mold will develop when dirt is found on the PVC window profile as a nutrient for fungi. The hard PVC from which the window is made is resistant to biological corrosion, while the wooden parquet at the threshold is not, moreover it can be biodegradable.

The next site analyzed in the article is the connection of the gable wall with the longitudinal (shielding) wall and the ceiling of the last storey in the insulated building in the OWT-67N technology (figure 8). In this connection, condensation is quite common, because the place is usually covered by curtains that limit air circulation. This situation took place in the apartment where the thermogram visible in figure 9 was performed. Analyzing the possibility of condensation of water vapor on the surface of the thermal bridge from the condition to the dew point, at room temperature of θ_i=19°C and humidity *RH* = 55%, surface condensation does not occur (figure 10). It does not exclude water vapor condensation on under other thermal and humid conditions. It can take place when the humidity inside the apartment increases due to cooking, bathing or drying.

This situation was confirmed on the next thermogram, assuming – as in the previous example – a temperature factor equal to 0.93. The condensation zone (mold infestation), after determining the isotherm for critical temperature θ_{sia} = 14.6°C is shown with arrows in figure 11. The range of possible condensation was confirmed by traces of mold visible in the thermogram (figure 8).

Figure 8. Photograph of upper corner connection gable wall – curtain wall with mold traces visible on the wallpaper

Figure 9. Thermogram of the upper corners with a visible temperature reduction in the corner

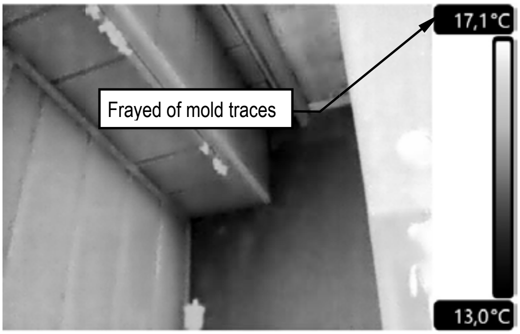

Figure 10. Thermogram of the site endangered by surface condensation in a room corner – a condition for dew point

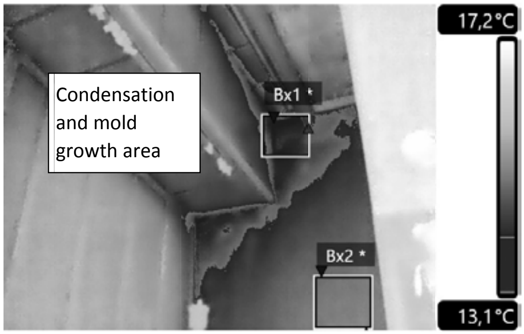

Figure 11. Thermogram of the site endangered by surface condensation in a room corner – a condition for critical temperature

Source: author's own work.

Another example of a place where moisture condensation and mold development can occur is the surface of the gravity ventilation duct in the room on the top floor (figure 12). As a result of the small chimney draft on the top floors, especially pronounced when the windows are tight, during fan operation in the kitchen hood or in the bathroom, the draft can be reversed in the channels without a fan (Wróbel, 2011). Such a case took place in the apartment on the top floor through which the ventilation duct ran in a reverse sequence. What is more, the analyzed flat had airtight windows without ventilators and was poorly ventilated. Outside air, with a temperature of – 2°C, flowing through the ventilation duct to the below apartment cooled the surface of the wall considerably (figure 13). This resulted in condensation of water vapor and mold growth. Such situations are quite frequent and take place when the windows are tight without efficient ventilators (Janińska, 2000).

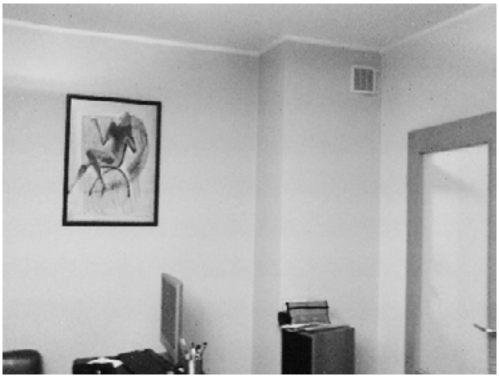

Figure 12. The natural ventilation channels in the room on the top floor of the building

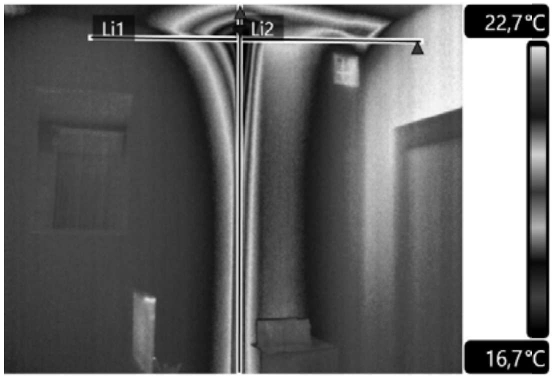

Figure 13. Thermogram of natural ventilation channels in the room on the top floor of the building

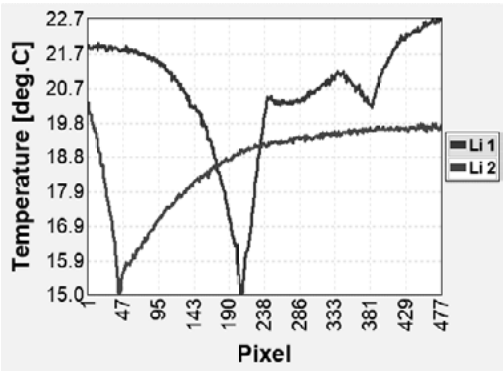

Figure 14. Temperature drop in the Li1 and Li2 profiles on the ventilation duct from Fig. 12

Source: author's own work.

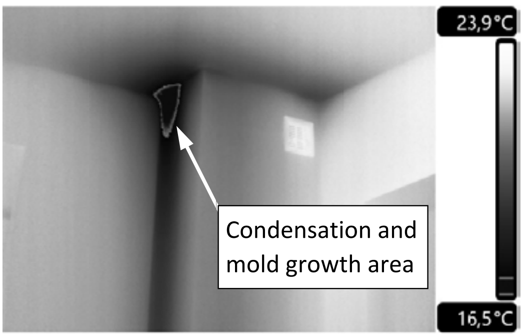

Figure 15. Thermogram of the place endangered by surface condensation in a room corner – a condition for dew point

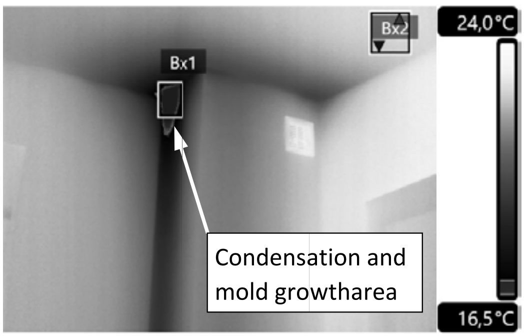

Figure 16. Thermogram of the place endangered by surface condensation in a room corner - a condition for critical temperature

The reach of the wall mold contamination zone with the ventilation duct coincided with the condensation zone (figure 15) determined from the condition for the dew point temperature (θ_s + 1°C) and the critical temperature resulting from the f_{CRsi} temperature factor (figure 16).

Different ranges of water vapor condensation zones shown on the thermograms (figures 6, 7, and 10, 11) result from the thermal and humidity conditions which occurred during the test. When changing the relative humidity *RH* or indoor air temperature θ_i, the range of moisture condensation zone and mold growth, determined from the condition on the dew point temperature, will be different.

Conclusions

Thermovision as a tool for detecting sites at risk of mold development has many advantages. It is a quick and non-invasive method. The advantages also include visual and graphical representation of the results of a large surface examination. The disadvantages include the need to take into account many factors affecting the interpretation of thermograms. In addition, suitable climatic conditions are necessary for correct measurements. The tests should be carried out with the possible temperature difference between the internal and external environment of minimum temperature 15°C. When registering and interpreting maps, knowledge about the construction of building partitions of the building being investigated and the experience of the thermal imaging camera operator is also important.

On the basis of calculations and processing of thermograms made, it can be stated that thermovision enables the detection of sites threatened by the development of mold fungi upon the determination of water vapor condensation areas. During field tests, it was confirmed that the most frequent places for mold development in dwellings are the partitions, where – as a result of temperature decrease and high humidity (no ventilation) – surface condensation occurs. Covering such places with furniture or curtains at the windows further increases the risk of mold infection by reducing air circulation.

During the site inspection of the buildings in industrialized technology, it was found that the improvement in "thermal quality" of housing estates by various thermomodernization treatments is not a sufficient measure to avoid the development of mold on the surfaces of partitions. The behavior of residents, who should take care of periodic airing of apartments has a huge impact, especially after the emission of a large amount of moisture. Ventilation can be facilitated by window ventilators, which should be installed in new windows.

Acknowledgements

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