Modeling of Dynamic Responses in Building Insulation

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Abstract. In this research a measurement systemwas developedfor monitoring humidity and temperature in the cavity between the wall and the insulating material in the building envelope. This new technology does not disturb the insulating material during testing. The measurement system can also be applied to insulation fixed ten or twenty years earlier and sufficiently reveals the quality of the insulation. A mathematical model is proposed to characterize the dynamic responses in the cavity between the wall and the building insulation as influenced by weather conditions.These dynamic responses are manifested as a delay of both humidity and temperature changes in the cavity when compared with the changes in the ambient surrounding of the building. The process is then modeled through numerical methods and statistical analysis of the experimental data obtained using the new system of measurement.

Keywords: *building insulation; modeling; dynamic response; statistical analysis; testing.*

1 Introduction

Buildings require high-performance insulation installed in the building envelope in order to maximize the return on investment. Water instrusion and weathering resulting in wet insulation can be caused by low performance of the building envelope and lead to costly preservation and restoration, excessive energy expenses, and inadequate indoor air quality. In addition, it can negatively affect the life span of the building and priceless assets contained in it.

The problem of the reliability of building insulation can be alleviated by utilizing immediate testing of both temperature and humidity in the cavity between the wall and the insulation, and the temperature in the ambient surrounding of the building. The space in the cavity is important. It needs to be monitored as it may provide suitable conditions for microorganisms. The growth of microorganisms has been established as a risk factor in building insulation. Testing once or twice does not show the instantaneous response to weather changes. The measurement series applied when using the new

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developed equipment maps the situation in the cavity without disturbing the inner conditions and clearly shows the delay in the response to outer weather changes.

Mathematical modeling using numerical methods and statistical analysis enables one to describe some aspects of the situation regarding heat transfer and the associated delay in the response of the building envelope, including the installed insulation. In many cases, however, the set of equations describes only an ideal situation. The collection of correlations can express the accuracy of the relationship between the real situation, whose description is based on real testing and measurement results, and its mathematical description [1]. Temperature-dependent material properties are usually tested on the material's surface as boundary conditions. The building wall has its typical value for heat flux, which depends on the material used to build the wall, among other things. A mathematical model can also be used to test the reliability of the thermal properties of the building envelope [2].

However, there is one extra problem when typical conditions appear in the space between the wall and the insulating material. This problem is usually connected with the process of condensation that has been established as a risk process in building insulation that can cause not only material destruction but also provide a suitable environment for the appearance of microorganisms. These aspects have motivated the initiation of the research project entitled "Detection and Management of Risk Processes in Building Insulation". This research is carried out at the University of Prešov in Prešov and Vienna University of Technology.

Dealing with building insulation, mostauthors usually stress aspects such as:

1. Economics: mostly building efficiency [3,4].
2. Safety and health: secured with some environmental aspects [5].
3. Process conditions such as heat flux and properties of porous materials ([6-8]).

Scientific investigations are often concerned with finding a way to describe a situation in order to meet each one of the abovementioned criteria.

Our part of the research project is concerned with experiments using a new method that can measure the humidity and temperature in the space between the wall and the insulation without disturbing the conditions in this cavity. The experiments can reflect a real situation and can also test older buildings with insulation that has been in use during many seasons of weather changes and with a high probability of mould appearance. The nature of unexpected weather changes makes a dynamic response analysis sophisticated and time-demanding. We used several numerical tools and statistical analyses for the dynamic response modeling.

2 Measurement Series Description

In this research, it was decided to test humidity and temperature conditions in the space between the wall and the insulation panels made of polystyrene, a porous building material with a thickness of 8 centimeters. Experimental trials were conducted using a new measurement system with equipment that was specifically developed, built and tested for this purpose (Figures 1 and 2). More details regarding the measuring equipment, its construction, properties and accuracy were reported in [9] and [6].

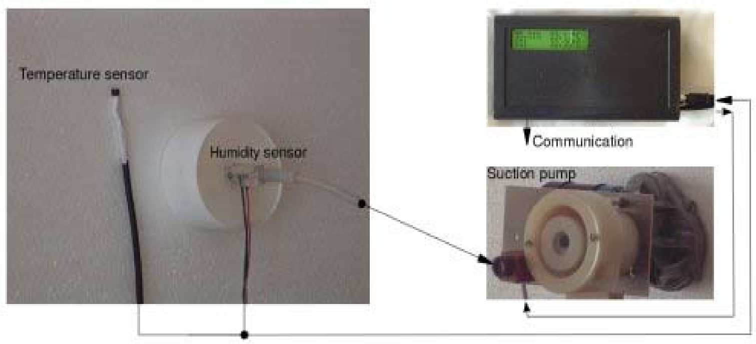

Figure 1 Measurement equipment used for testing the humidity and temperature levels in the space between wall and polystyrene insulation panels and also in the ambient surrounding outside of the building.

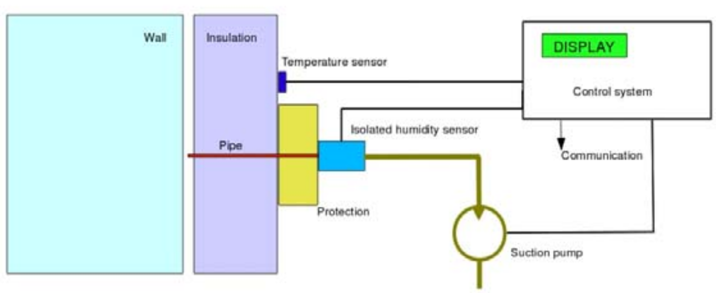

Figure 2 Schematic representation of the measurement equipment with its mutual connections.

The experiment was held on a building with walls made of bricks, heated regularly and with a permanent inner temperature of 20 °C. The building whose building envelope cavity conditions were tested, is situated on the northern part of the globe (49° 00’00”N, 21°14’00”E), 255 m above sea level. The measurements were carried out every 30 min, resulting in more than 980 values, as shown in Figure 5, during the time interval from January 17, 2012 to February 20, 2012, in the winter time.

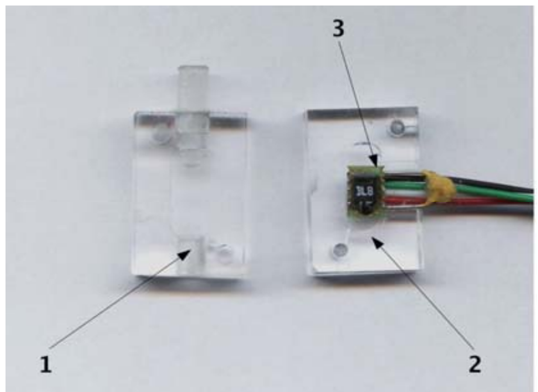

Figure 3 Sensor SHT15 with the chamber. (1) Upper part of the chamber, (2) lower part of the chamber, (3) sensor.

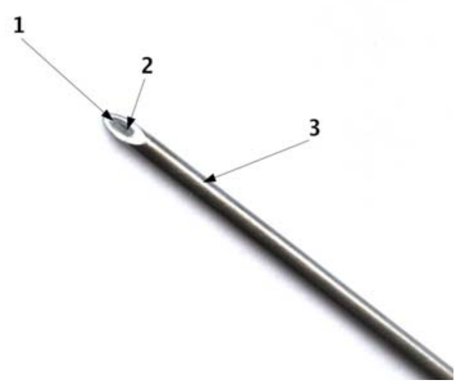

Figure 4 The pipe pierces through the panel of insulation material and transports the air sample to the chamber with the sensor. (1) Hole through the pipe, (2) polypropylene, (3) stainless steel.

Two sensors monitored the temperature and humidity values. One sensor (SHT15 – Figure 3) was placed into a chamber and connected with the cavity between the wall and the insulation using a special pipe (Figure 4) to test both temperature and humidity. The pipe is made of two materials. Material 2, directly around hole 1 in Figure 4, is polypropylene of low heat conductivity so as not to influence the properties of the sucked air sample. Material 3 is stainless steel, hard enough to pierce the panel of insulation material.

Another sensor monitored the ambient temperature of the ambient surrounding of the building in order to verify if the influence of outer weather changes was not too strong. Figure 1 also illustrates the SHT15 sensor placed in the chamber made of a material with low heat conductivity. Air is drawn into the chamber and then kept there for 30 seconds until the display shows the humidity and temperature values. The sensor requires more than 8 seconds to show the proper humidity value and from 5 to 30 seconds to show the proper temperature value,depending on the direct temperature differences. Therefore, 30 seconds is counted as sufficient for this purpose. A suction pump connected to the chamber with a tube was built based on the peristaltic principle in order to guarantee a constant amount of sucked air for each sample.

3 Characteristics of the Values Obtained During Measurement

The heat transfer is also expected to be influenced by the presence of moisture in both wall and insulation. Condensation can create special conditions in the space between the wall and the insulation. When vapor leaves the insulation or the wall through the insulation material, it carries latent heat with it. Polystyrene panels are specific in that they are water resistant. Therefore, they have a tendency to keep the water in the space between the wall and the insulation, which can cause problems later on, for instance in the form of material destruction and condensation. The condensation process also creates suitable conditions for the appearance of microorganisms. Therefore, it is important to test buildings with long-term insulation without disturbing the conditions in the cavity in order to reveal the real situation.

A graphical representation of both the humidity and temperature values in the cavity between the wall and the insulation and the temperature in the ambient surrounding of the building in their mutual coherence is shown in Figure 5. The obtained values were also used for a dew point calculation to find out the possible condensation process. Neither measured values nor calculations showed formation of condensation, which is typical for buildings heated regularly and with their insulation installed properly.

The problem of high humidity in the cavity between the wall and the insulation panels or of a high moisture level of building materials can appear for instance

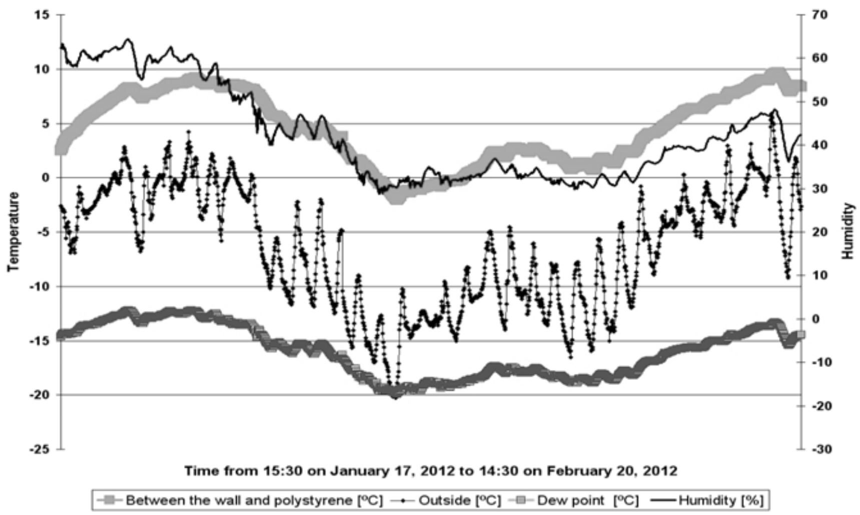

Figure 5 Graphical representation of the values obtained during the measurement series: humidity and temperature in the cavity between wall and insulation and temperature in the ambient surrounding of the building.

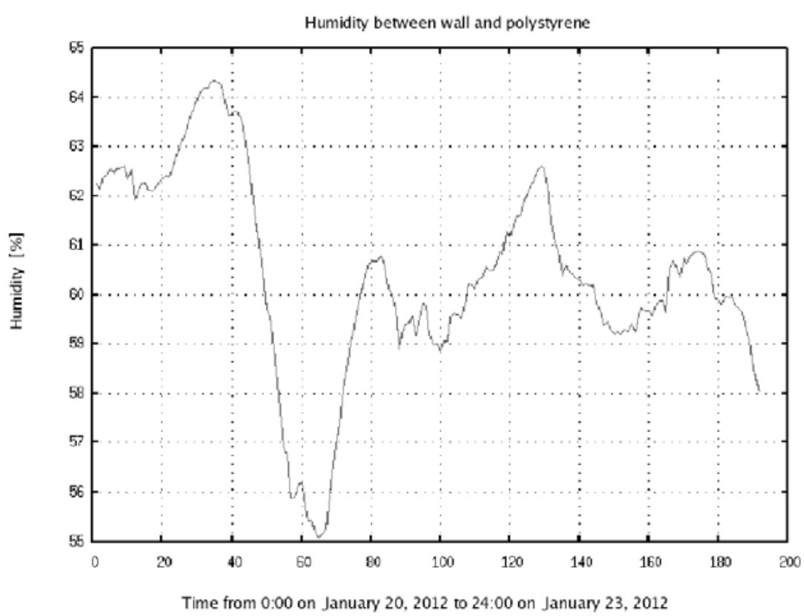

Figure 6 A graphical representation of humidity values in the cavity between wall and insulation material in detail.

in case of moisture spreading from the building's foundations or through the holes for the electricity wires where they are improperly isolated. Other humidity problems can appear over time when snow melts or as a result of flooding. The condensation problem also occurs in cottages that are usually heated only seasonally, for instance only during the weekends in the winter time.

The graph in Figure 6 comprises a detailed representation of the humidity values in the cavity between the wall and the insulation, obtained during the measurement series using the new developed testing equipment. The graph shows the amplitude range with remarkable values that are important for determining the level of risk.

4 Modeling of Dynamic Responses

The dynamic responses appear as the reaction delay of the temperature in the cavity between the wall and the insulation in response to the temperature in the ambient surrounding of the building (Figure 5). The reaction in response to external temperature changes has been the subject of some studies, for instance [10], in which phase function modeling based on a curve-fitting approach was introduced and compared with Mie theory results. The subject was a radioactive energy fraction. Wang and Tan in [11] analyzed heat transfer for temperature prediction in an insulated steel panel exposed to fire. They mainly used a step function for the analytical expression of the temperature response.

4.1 Methodology and Algorithm Determination

The temperature in the cavity between the wall and the insulation is dependent on the temperature outside the building. Dependence is also reflected in the time delay in the response to external temperature changes measured in the ambient surrounding of the building not to be very influenced by strong wind gusts.

The graphic representation in Figure 7 illustrates the time delay between the amplitudes of the temperature values in the space between the wall and insulation and the ambient surrounding of the building. Figure 8 shows the relationship between the time and the amplitudes of the temperature values using the least squares method.

The amplitudes of the temperature values (Figure 7) acquire different values also according to the slope defined by the sharpness of the graph's curve. Statistical analysis represented by correlations proved a relationship between the difference in temperature value amplitudes as time delay response and the slope that illustrates the sharpness of the changes in external temperature.

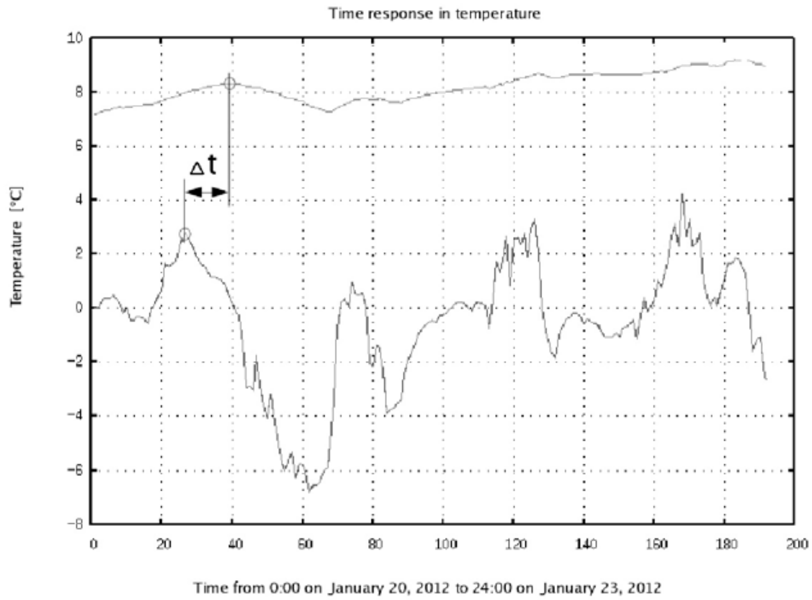

Figure 7 Graphical representation of the relationship between the temperature values in the space between wall and insulation and the ambient surrounding of the building.

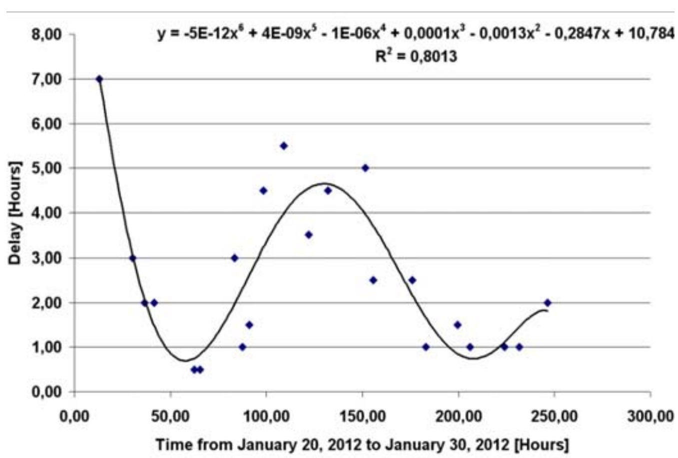

Figure 8 Graphical representation of the relationship between the temperature values in the space between wall and insulation and the ambient surrounding of the building.

The algorithm for the expression of the dynamic responses using the correlation in the least square method was set as follows:

1. Determine the amplitudes of the temperature values in the ambient surrounding of the building according to the measurement results.
2. Determine the amplitudes of the temperature values in the cavity between the wall and the insulation according to the measurement results.
3. Determine the distance (Δt) between the *x*-coordinates for each couple of mutually corresponding amplitudes.
4. Calculate the sharpness of slope for every connecting line between the minimum and maximum amplitudes of the external temperature values using the formula:

$$k = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sum_{i=1}^{n}(x_i - \overline{x})^2} \tag{1}$$

   where $\overline{x}$ and $\overline{y}$ in all formulas stand for the mean values of x and y respectively.
5. Set the correlation between amplitude distances and sharpness of slope.
6. Control accuracy of obtained results using statistical analysis.

4.2 Statistical Analysis for Modeling of Dynamic Responses

The mutual relationship between the sharpness of slope is expressed using Formula (1). The distance between the *x*-coordinates of the amplitudes of the temperature values according to the graphical representation in Figure 7 is the subject matter of the following graphs.

The distances between the *x*-coordinates of the amplitudes of the temperature values according to the graphical representation in Figure 7 are expressed as the y_i-coordinates of the points in Figures 9 and 10 and the mean delay in the response of the temperature in the cavity between the wall and the insulation to changes in the external temperature.

In our statistical analysis, we checked if the values expressed in the graphical characteristics in Figure 9 correlated, using Formula (2) for obtainingthe value of Pearson's coefficient:

$$r_{xy} = \frac{\sum_{i=1}^{n} x_i y_i - n.\bar{x}.\bar{y}}{\sqrt{\left(\sum_{i=1}^{n} x_i^2 - n.\bar{x}^2\right).\left(\sum_{i=1}^{n} y_i^2 - n.\bar{y}^2\right)}} \tag{2}$$

The obtained value for Pearson's coefficient is:

r_{xy} = - 0.6891

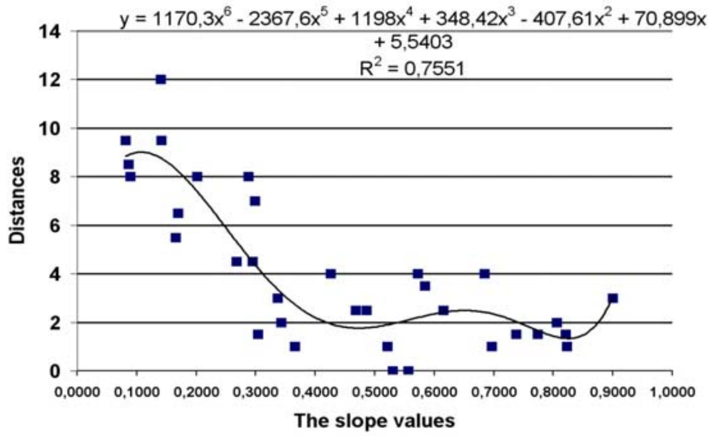

Figure 9 Graphical representation of the mutual relationship between slope sharpness and distance between the *x*-coordinates of the amplitudes of the temperature values (x_i,y_i) and the trend line of polynomial dependence given by Formula (2).

When testing the relationship given in Formula (3), using the quintile value on the level of significance for alpha = 0.05, a correlation was proved.

$$\frac{|r_{xy}|\sqrt{n-2}}{\sqrt{1-r_{xy}^2}} > t_{1-\frac{\alpha}{2}}(n-2) \tag{3}$$

The correlation using the least square method is expressed in both-ways polynomial (Figure 9) and hyperbolical (Figure 10) dependencies. The obtained coefficient values for the polynomial dependence of the common correlation are then expressed as the polynomial of the sixth degree:

$$y = 1170.3x^6 - 2367.6x^5 + 1198x^4 + 348.42x^3 - 407.61x^2 + 70.899x + 5.5403 \tag{4}$$

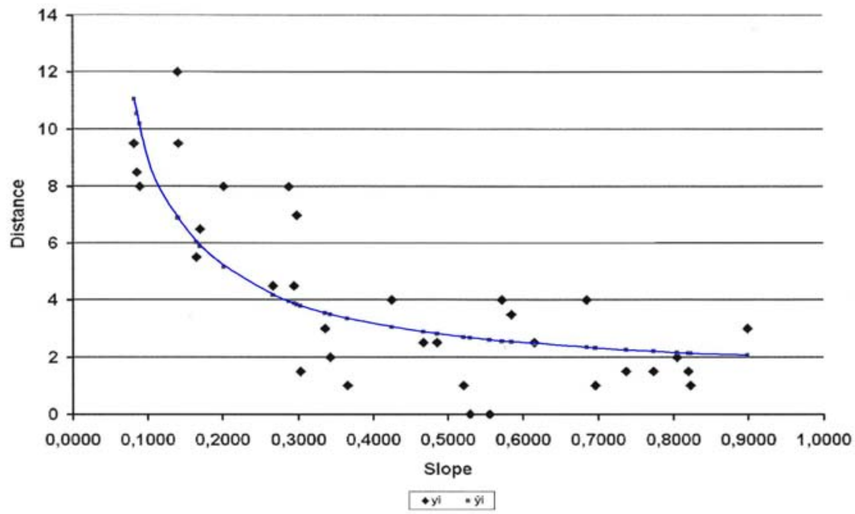

Figure 10 Graphical representation of the mutual relationship between slope sharpness and distance between the *x*-coordinates of the amplitudes of the temperature values (x_j,y_j) and the trend line of hyperbolical dependencies given by Formula (5) and passing through the points with coordinates $(x_j, \hat{y}_j)$.

with the value of determination index:

$$i^2 = 0.7551$$

where *x* represents the value of the slope for the line connecting the minimum and maximum amplitude of the temperature values in the ambient surrounding of the building according to Formula (1), and *y* is the expression of the approximate distance Δt between the *x*-coordinates of the amplitudes of the temperature values in the cavity between the wall and the insulation and the external temperature, according to Figure 7.

The relationship that is based on the hyperbolical dependency is expressed as the trend line in Figure 10 and analytically through the following formula:

$$y = 1.159396895 + \frac{0.803507775}{x} \quad (5)$$

The index of correlation is yielded by using the formula:

$$i_{yx} = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{y}_j - \overline{y}\right)^2}{\sum_{i=1}^{n}\left(y_j - \overline{y}\right)^2}} \tag{6}$$

$$i_{yx} = 0.8043 \; .$$

5 Conclusion

The model of dynamic responses describes the delay in changes of the temperature values in the cavity between the wall and the insulation as a reaction to changes in the external temperature in the ambient surrounding of the building. To map real temperature values in the cavity between the wall and the insulation, new measuring equipment was constructed. The equipment enables one to test the properties of the air in the cavity without disturbing its conditions.

Numerical methods showed how the response structure of the temperature in the cavity at any given time depended on the history of the previous temperature changes in the external temperature. To describe the history of the temperature changes, the sharpness of slope between the amplitudes in the graph expressing the temperature values in the ambient surrounding of the building was calculated.

When the slope is sharper, there is a more remarkable response: an almost immediate change of the temperature values in the cavity between the wall and the insulation. This mutual relationship can be expressed using Formula (5). Otherwise, the temperature in the cavity reacts only slightly to changes in the external temperature.

Testing the insulation quality using the developed measurement equipment can also show the heat transfer and reveal if the insulation has been damaged. If the insulation works properly, the humidity and the temperature changes in the ambient surrounding of the building directly affect the humidity level, but there is not a direct remarkable change in temperature in the space between the wall and the polystyrene insulation material. In future research, we intend to test some new building materials, especially regarding their specific properties.

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