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Determination of Condensation and Its Effect On Insulation and Wall Envelop Layers

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ABSTRACT

The condensation, occurs between the building envelope layers, is important for both human health and the functioning of the layers. Freezing of the condensed water in cold weather regions like 3rd degree-day locations means another solid layer that creates freeze-thaw effect. In this study, the amount of condensation between layers for 3 wall types is investigated in Kütahya. The condensation phenomena are determined by Glaser Diagram Method and the condensation amount is calculated by considering climatic data. Wall 3 gives the best result and that one has 0.001696833 kg/h.m^2 at 0 ºC, it is 0.002142743 kg/h.m^2 at -21 ºC condensed water amount due to low outside temperature.

1. INTRODUCTION

Energy efficiency studies especially in buildings became popular after the European Green Deal is signed in developed countries [1]. The energy consumption in the building sector constitutes nearly 30% of the total global energy consumption [2]. Therefore, there is a huge potential to reduce energy consumption in buildings with energy efficiency studies [3]. One of the main application in a building is insulation to minimize the heat losses. It is calculated that 80% of the energy is consumed for heating, and cooling in buildings [4] so insulation is a common way to reduce the energy bill for a building envelope. Additionally, proper insulation might be used against condensation. The air in a room hits a surface with a temperature below its dew point; the water vapor in the air condenses and causes surface condensation. Condensation causes problems, such as mold, corrosion, material wetting, icing, and warping, and indoor condensation must be minimized [5]. Average temperatures are considered while insulating but the temperatures might drop below the seasonal average. This leads to condensation between the building envelopes layers especially at cold weather [6]. Condensation between the layers causes mold formation between the external wall layers and resulted in a poor performance of the insulation material [7]. When the insulation loses its characteristic, heat loss and more condensation take place. The number of layers in the building envelope also brings the risk of condensation [8]. Insufficient or damaged insulation will let water vapor diffusion between wall layers. Organic thermal insulation materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS) are used in buildings as they have low thermal conductivity and low cost. The given materials are likely to be affected by severe cold weather conditions [9, 10] such as freeze-thaw due to water vapor. As temperature goes below zero, the water turns into ice and expands by 9% in volume [11, 12] and the frost-heaving force will cause the destruction of insulation material and/or other layers. In a study, the variation of the insulation thickness was analyzed in Bitlis and it was found out that as the relative humidity differs, the risk of condensation on the wall also increases. Another outcome was the ice applies a push force on the insulation and plaster. This repulsion could cause space between these envelop layers in time. This gap also resulted in the external plaster or insulation to shed [13]. It was proved in another study that freeze-thaw and temperature-drop occurred mainly in the thermal insulation layer. In addition, the annual energy consumption of the insulation system with freeze-thaw was calculated as on average 1 kWh/m^2 of surface area higher than that without freeze-thaw [14]. In cold regions, the surface of concrete structures is prone to ice and snow, leading to serious freeze–thaw damage [15] and the damage caused by freeze–thaw cycles can lead to a reduction in the compressive and tensile strength of the concrete [16]. In some studies, various materials are tried as insulation material like hydrophilic mineral wool. Performance of a concrete building envelope was analyzed for freezing cycles during the five-year period. Hydrophilic mineral wool material presented the most prospective solution for the thermal insulating layer in a building envelope [17]. They made a conclusion to a specific insulation material depending on their analysis, but they did not compare various thickness layers of insulation material. Some other studies concentrated on the freeze-thawing damage and effects on building thermal physical parameters and energy consumption. The expanded polystyrene (EPS) was numerically analyzed as an exterior surface of the envelope. One of the results showed that the freezing of the moisture in the building envelope would affect the insulation performance seriously. EPS was analyzed but the behavior of the insulation at various temperatures should have been included to this study [18]. Additionally, an interesting study was made on concrete to modify the concrete's water resistance. It was stated that the strength of this new concrete was only reduced by 12% after 20 freeze-thaw cycles, showing a far better result than traditional cement concrete. Thus, laboratory modified concrete can be used as a good insulation material for frost resistant buildings. This composite looks preferable on a laboratory scale trial, but the economic feasibility of this new composite concrete is needed to be assed in details. Both investment and operational cost comparison with traditional insulation materials should be done to be able to make a decision [19]. Some recent studies also proposed that freeze-thaw could cause degradation of thermal and mechanical properties of insulation and even malfunction during severe weather conditions. Some modern insulation materials have been developed such as closed cell foam, vacuum insulation panel (VIP), gas filled panel, aerogel, and phase change materials with higher and better performance comparing with traditional ones [20, 21, 22]. Silica aerogel products are often mentioned as promising materials to increase the thermal resistance of the building envelope [23]. Existing studies are concentrated on the investigation of the effects of newly developed materials at the external wall layers [24]. However, considering the climate data, the amount of condensed and frozen water, different layers, and various temperature effects is missing in this study. This paper highlights all these points with the free-thaw problem. To achieve this aim, three different wall envelopes are analyzed with Glaser Diagram Method. The calculations are compared for three options and the best performance is identified. A formula is created from various outside temperatures for this best wall envelope to calculate the amount of condensed water amount in Kütahya for a specific outside temperature. Annual temperature data of Kütahya in 2020 is analyzed and used in this study. This study presents a new formula to calculate condensed water amount due to temperature differences between building enveloped layers. This study can be applicable for another location if the temperature data is known, which makes this paper valuable in terms of sharing knowledge.

2. MATERIAL AND METHOD

In this study, three types of wall envelopes are used and these envelopes can easily be seen in Kütahya. All three walls have the same insulation material (5 cm thick XPS panel) with a conduction coefficient of 0.03W/mK. Initially, walls are assessed to determine the condensation level to find out the best one.

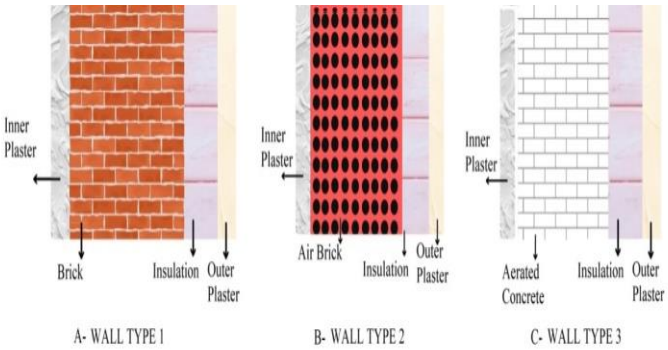

Figure 1. Wall envelope layers

Wall 1: In this wall type, the masonry brick is used before energy efficiency studies started. The wall is given in Figure 1A and the brick thickness is 0.135 m. Wall 2: After the increase in the use of perforated bricks in the 70s, thermal insulation of buildings using such walls are tried to prevent thermal leaks. The wall component using this brick type is shown in Figure 1B and the air brick thickness is 0.19 m. Wall 3: In recent years, aerated concrete has been preferred due to its thermal advantages. Aerated concrete material is very good in thermal insulation thanks to its porous structure. However, the porous structure also increases the mass transfer. The aerated concrete wall is shown in Figure 1C and the aerated concrete thickness is 0.2 m.

2.1 Detection of the Critic Temperatures for Condensation Analysis in Each Wall Type with Glaser Diagram Method

In this method, first the wall surface temperatures in the intermediate layers and then the condensation amount between the wall layers are calculated. The calculation method is explained in [25, 26]. Additionally, the equations of energy and mass conservation for heat and mass transfer through the walls can be found in [27, 28]. Each wall layer's surface temperatures are calculated and then the water vapor partial humidity at the surface of each layer is determined by equation 1 and 2 [29].

$$If\ T < 0\ P_s = 610.5.e^{\left(\frac{21.875.T}{265.5+T}\right)}. \quad (1)$$

$$If\ T \geq 0\ P_s = 610.5.e^{\left(\frac{17.269.T}{237.3+T}\right)}. \quad (2)$$

As addressed in several literature, water vapor flows is through a material from a high pressure to a low pressure, or the warm side to a cold side of a wall. There will be condensation between the wall layers especially at the insulation layer. This liquid layer may freeze and increase in volume when the air temperature drops below 0 ºC, especially in cold climates like 3rd and 4th degree-day zones in Turkey [30, 31]. This volume increase occurs as expansion in the direction in which the layer can do. Figure 2 shows an example for solidification expansion of unit area.

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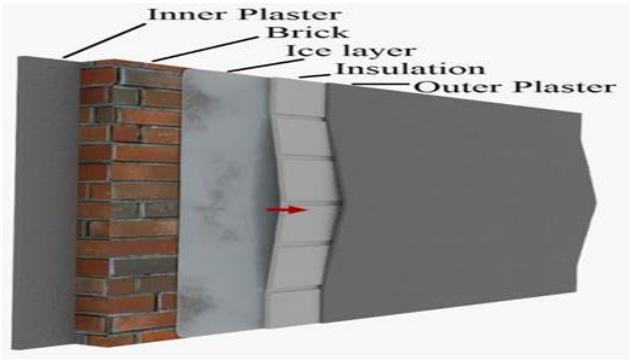

Figure 2. The ice layer that formed between layers of wall

The expansion caused by the freezing of the condensed water layer creates a thrust on the insulation and plaster layers. The thrust can be described by the deflection (displacement) that occurs in the insulation layer. This displacement can escalate as the condensed water amount increases, which can be calculated by equation (3).

$$dV = A.dx. \qquad (3)$$

The change in the x-direction per unit area is calculated with Eq. 4 as the volume is a function of mass;

$$dx = \frac{\dot{m}.\Delta\rho}{A}. \qquad (4)$$

Here, $\dot{m}$ is the condensation amount in (kg/h). Δρ is the density difference of the condensing fluid. A is the unit area is 1 (m^2) and dx is the thrust applied to the insulation layer in one hour by the freezing fluid in (mm/h). Finally, the hourly condensed water amount can be calculated by Eq. (5) [32, 33].

$$\dot{m} = \delta_0\left(\frac{p_i - p_{sw}}{S_{d,T} - S_{d,sw}} - \frac{p_{sw} - p_d}{S_{d,sw}}\right). \qquad (4)$$

Here, P_i is partial pressure of water vapor at inner surface of the wall (Pa), P_d is partial pressure of water vapor at inner surface of the wall (Pa), P_{sw} is the partial pressure of water vapor where condensation begins (Pa). δ_o is the water vapor permeability, which is assumed to be constant 2.10-10 (kg/msPa) [34]. $S_{d,sw}$ is the permeance of the wall layers where condensation begins and $S_{d,T}$ is the total permeance of the wall. $S_{d,T}$ can be calculated by using Eq. (6);

$$Sd = \mu . d. \qquad (6)$$

μ is the vapor diffusion resistance factor and d is the thickness of the layer (m).

3. RESULT AND DISCUSSION

The condensed water amount is needed to be determined so the thickness and thrust of the ice can be assessed. This calculation is done for three wall types separately with Glaser Diagram Method and Figure 3, Figure 4 and Figure 5 illustrate the results of sthis methodology. In this method, the blue lines in the figures are theoretical saturation pressure of vapor passing through the wall. The dots on the broken red line illustrate the partial pressure of water vapor at layer surfaces. If the red dot touches the blue line, that means the pressure drops below saturation pressure and condensation begins. In Wall 1, standard masonry brick type is selected. The critical outside temperature is 0°C and the relative humidity both indoor and outdoor is taken 80%. Masonry brick is commonly used in construction in Turkey. It is seen that condensation begins outside the insulation from 0°C. It can also be stated that the amount of condensation increases as the atmospheric temperature decreases (Fig. 3).

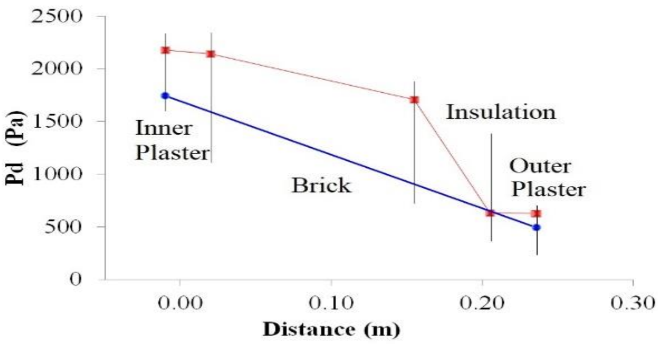

Figure 3. Internal condensation analysis for Wall 1 at 0°C, φin= φout= 0.8

Wall 2 (air brick) is also widely used in construction. The analysis showed that Wall 2 has also condensation (Fig. 2).

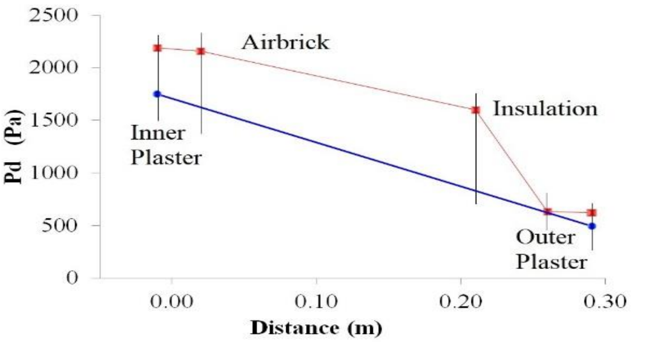

Figure 4. Internal condensation analysis for Wall 2 at 0°C, φin= φout= 0.8

In some buildings, aerated concrete component (Wall 3) with a lower heat transfer coefficient is also preferable. Wall 3 has condensation at the outer side of the insulation where the conditions are the same with Wall 1 and Wall 2. In all 3 cases, condensation below 0ºC means that the condensed water vapor freezes and affects the insulation layer performance. Water vapor begins to occupy space between the layers once the condensation starts freezing.

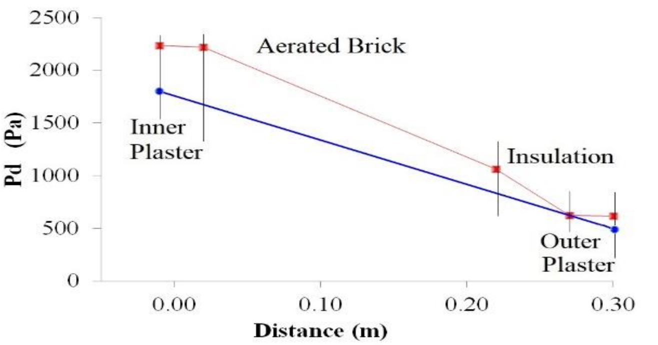

Figure 5. Internal condensation analysis for Wall 3 at 0°C, φin= φout= 0.8

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All analysis proved that there will be a solid layer of ice which is not considered while choosing the insulation material or the thickness of the insulation material. The ice layer deforms the insulation material and pushes the insulation layer, resulting in displacement. It can also be said that as the indoor humidity increases, the condensation intensity also increases. Controversially, an increase in the relative humidity of the outdoor environment causes a decrease in the condensation amount. Another factor that increases the condensation between the building envelope layers is the outdoor temperature drop. A decrease in atmospheric temperature increases condensation [35]. Among all envelopes, Wall 3 gives the best results, as it has the least water condensation amount. This analysis is done for 0 ºC ambient temperature, the temperature goes further below zero in Kütahya. In order to check the condensed water amount, the above calculations for various outside temperature level from 0 ºC to -21 ºC is done for Wall 3. Results are presented in Table 1.

TABLE 1.
Condensed water amount related to ambient temperature

Ambient Temperature	Condensed Water Amount
0	0,001696833
-1	0.001742621
-2	0.001784777
-3	0.00182354
-4	0.001859133
-5	0.00189177
-6	0.001921647
-7	0.001948954
-8	0.001973866
-9	0.001996549
-10	0.002017157
-11	0.002035837
-12	0.002052725
-13	0.002067949
-14	0.00208163
-15	0.00209388
-16	0.002104803
-17	0.002114498
-18	0.002123056
-19	0.002130564
-20	0.002137102
-21	0.002142743

These values (Table 1) put into a curve fitting given at Figure 6 and a formula created to use for a Wall 3 type building in Kütahya.

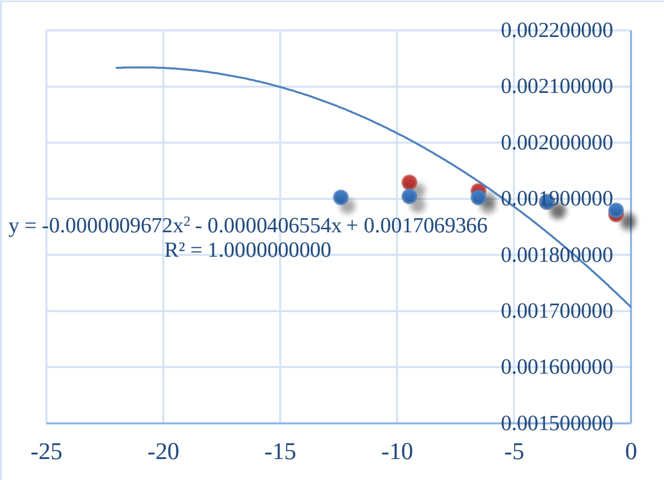

Figure 6. Curve fittings for various temperature values

This formula can be used to find the amount of condensed water at a specific outside temperature for a Wall 3 type enveloped building in Kütahya.

$$y = -0.0000009672x^2 - 0.0000406554x + 0.0017069366 \quad (7)$$

In this equation y stands for condensed water amount, and x stands for the outside temperature. The condensed water freezes under severe weather conditions and create a solid layer. This layer stays on the cold site of the insulation and negatively affect the insulation. In a specific time, the condensed water amount between the enveloped layers at the Wall 3 buildings can be calculated with this equation (Eq. 7). As it is given in Table 1 and Figure 6, the condensed water amount increases as the outside temperature drops.

In existing literature, there are some studies mentioning the negative affect of cold weather conditions on insulation material but this paper created a formula to calculate the condensed water amount. Recent studies mentioned that condensed water turns into ice and ice pushes the insulation and plaster. This study results show same results with these researches. In this paper, three different wall types are analyzed and one of them represent a better result in condensed water amount. Having compared three wall options make the study findings valuable. In other studies, different insulations materials or various thickness of insulation materials are studied but there is no formula given in these papers. In this study, a formula is created to calculate the condensed water amount for a very common building envelope in Kütahya.

4. CONCLUSION

Insulation of a building for the purpose of lesser the energy consumption content is a widely accepted application in nowadays. However, analyzing the condensed water due to drastic temperature drops between buildings envelop layers is the next era for building energy efficiency studies. The effect of insulation thickness on water condensation amount is not the main perspective of this research. It is known that there will some condensation and this condensed water might freeze but there is no direct formula to find the condensed water amount between envelop layers. In this paper, condensation analysis is made with Glaser Diagram Method. Results are compared and Wall 3 gives the best insulation performance in terms of condensed water amount. Wall 3 is taken as an example to

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generate condensation water amount at below zero temperatures. The amount of water is calculated as 0.001696833 kg/h.m^2 at 0 ºC, and it is 0.002142743 kg/h.m^2 at -21 ºC. The created formula will help engineers to find the condensed water amount for a Wall 3 type building in Kütahya. The condensation has been observed even when the external ambient relative humidity is 50% in the buildings using masonry bricks. Here it can also be stated that as the indoor and outdoor relative humidity increases, the amount of condensation increases. In addition to the traditional insulation materials, a variety of new high performance thermal insulation materials have been developed in recent years like gas filled panel, aerogel, and phase change materials. In this study, traditional insulation material is used. Some other insulation material performance should also be assessed especially the new generation insulation materials like aerogel and/or phase changing material. This study can also be repeated for some other regions for colder conditions with some other building materials. The thickness of the materials that are constructing the building enveloped can be also changed to see the effect of the insulation performance and condensing water amount. Especially, the thickness of the new types of insulation materials effect on condensed water amount is one of the topics that the authors are intending to carry on a further research on.

NOMENCLATURE

EPS	Expanded Polystyrene
Eq.	Equation
kWh	Kilowatt-hour
m^2	Square meter
Pa	Pascal
VIP	Vacuum Insulation Panel
W/mK	Watt/Meter Kelvin
XPS	Extruded Polystyrene

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BIOGRAPHIES

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