Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1593337

Open Access Journal
e-ISSN: 2619 - 8991

Research Article
Volume 8 - Issue 3: 891-898 / May 2025

INVESTIGATING THE IMPACT OF INSULATION THICKNESS ON CONDENSATION LEVELS: A CASE STUDY IN SİVAS, TÜRKİYE

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Abstract: This extensive research has resulted in the ingenious design of an intelligent composite wall, which incorporates internal and external thermal insulation to effectively deal with the cold climate conditions prevalent in Sivas, Türkiye. Outdoor temperatures in this region drop significantly at night, requiring effective thermal management solutions. The main focus of this research is to determine the minimum insulation thickness required to prevent surface condensation on the walls, which can cause potential problems. In particular, the study helps to identify the effect of thermal insulation on these variables through a series of elaborate and precise heat and mass transfer calculations, rigorously carried out over a range of different scenarios, including indoor and outdoor temperature conditions and variations in relative humidity. The results of such extensive analysis clearly show that the effectiveness and efficiency of thermal insulation becomes increasingly pronounced and evident as the indoor relative humidity exceeds the 70% threshold. In situations where the internal relative humidity is low, the need for increased insulation thickness approaches negligible or minimal levels. Significantly, the comprehensive analysis shows that when the outdoor relative humidity is increased significantly, from 50% to 80%, there is an inverse and measurable increase in the water vapour partial pressure in the external environment. An increase in the water vapour partial pressure results in a reduction in water vapour transmission and therefore reduces the possibility of condensation in that environment.

Keywords: Condensation, Thermal insulation, Cold climate, Relative humidity

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Received: November 29, 2024
Accepted: April 30, 2025
Published: May 15, 2025
Cite as: Aktemur C., Çakır MT. 2025. Investigating the Impact of insulation thickness on condensation levels: A case study in Sivas, Türkiye. BSJ Eng Sci, 8(3): 891-898.

1. Introduction

Following the signing of the European Green Deal in developed nations in 2020, there has been a notable surge in energy efficiency research, particularly concerning buildings. The building sector alone contributes nearly 30% to global energy consumption, highlighting substantial potential for energy conservation through efficiency measures. Among these, insulation stands out as a primary application within buildings, aimed at minimizing heat losses. Given that heating and cooling operations constitute approximately 80% of a building's energy consumption, insulation emerges as a widely adopted strategy for reducing energy expenditures. Additionally, appropriate insulation can be used against condensation (Çağman and Ünver 2023). Condensation is the process by which a gas turns into a liquid when a substance in the liquid phase comes into contact with a substance in the gas phase. This phenomenon can occur naturally as a result of the cooling of water vapor in the atmosphere, or it can occur when moisture leaking into a room hits a cold surface. Condensation on building walls often occurs as a result of water vapor coming into contact with the cold surfaces of building materials. In particular, factors such as inadequate insulation or wrong choice of building material can increase the risk of condensation. Condensation not only damages building materials, but can also reduce indoor air quality and promote mold growth, which can cause serious health and cost problems for both building owners and occupants (Kaynaklı et al., 2018).

Upon reviewing existing literature, it is apparent that research focusing on the examination of wall condensation is somewhat scarce. In a study conducted by Kaynakli et al. (2018), the optimization of thermal insulation thickness for building exterior walls was explored, incorporating various insulation methods with equivalent thermal resistance while considering condensation factors. Their investigation aimed to ascertain the minimum insulation thickness, known as the optimal insulation thickness, necessary to prevent condensation within the building structure. Results indicated that the optimal insulation thickness tended to increase with rising internal temperature, internal relative humidity, and external relative humidity. Notably, the type of insulation method employed was found to have minimal impact on the optimal insulation thickness under conditions of low to moderate indoor relative humidity. Furthermore, the study revealed that external insulation applications generally yielded superior outcomes in scenarios characterized by high internal and external relative humidity levels. Arslan and Kose (2006) conducted a comprehensive investigation into optimal insulation thickness, considering condensation dynamics in existing structures within Kütahya, renowned for its cold climate among Turkish cities. Their analysis extended to assessing the impact of condensing vapor on exergy. Through optimization processes, they derived optimal insulation thicknesses of 0.060, 0.065, and 0.075 meters, achieving energy savings rates of 74.9%, 76.3%, and 78.8%, respectively, across varying internal temperatures of 18, 20, and 22°C. Consequently, notable reductions in air pollutants were realized. Yamankaradeniz (2015) endeavored to minimize thermal insulation thickness, accounting for condensation risks on exterior walls. Findings indicated a correlation between increased indoor temperature, relative humidity, and outdoor relative humidity with augmented insulation requirements, while outdoor temperature increments led to decreased insulation needs. The researcher highlighted the potential risk of condensation on inner or outer insulation surfaces resulting from alterations in vapor diffusion resistance of insulation materials. Kon and Caner (2022) delved into the mold and moisture susceptibility of exterior walls, evaluating six wall types and three insulation materials. Their analysis encompassed uninsulated and insulated walls, considering moisture and mold proliferation attributed to dew point temperatures. Optimal insulation thicknesses varied, with hemp wool and hollow brick presenting the highest values for electrical energy sources. For insulated walls, the study identified critical internal humidity thresholds triggering mold and moisture formation as 78% in Izmir and 69% in Erzurum. Aelenei and Henriques (2008) aimed to delineate external environmental conditions conducive to condensation formation on building surfaces. Recognizing the sensitivity of building exterior temperatures to convective and radiative fluxes, their investigation entailed a comprehensive analysis of convective and radiative heat transfer coefficients across diverse climate scenarios and building envelope characteristics. Results underscored the pivotal roles of convection and air moisture content in driving surface condensation on building facades.

Bellia and Minichiello (2003) introduced TMCE (Thermal and Moisture Control for Envelopes), a user-friendly software tool designed for swift and straightforward assessment of the thermal and moisture dynamics of building components. Their analysis adhered to the European Standard ISO 13788:2001. In instances of wintertime condensation, the software facilitated computation of condensed vapor volumes, alongside evaluating the feasibility of complete moisture removal during warmer periods. You et al. (2017) endeavored to elucidate the temporal patterns of moisture condensation on interior surfaces within buildings located in high-humidity climates, employing a combination of numerical and experimental methodologies. A test chamber model was established to forecast air leakage's heat and moisture distribution, with simulation outcomes from FLUENT software juxtaposed against experimental findings. Their investigation scrutinized the influences of outdoor air temperature, humidity, and wind speed on moisture condensation, revealing significant impacts on condensation onset, duration, and intensity. From experimental data, they developed two regression equations delineating the interplay between indoor air temperature, humidity, and air leakage factors. Cho et al. (2016) integrated TRNSYS simulation with TRNFLOW to assess year-round condensation dynamics within an office building in Tokyo, Japan, even during periods when the air conditioning system remained inactive. Their evaluation considered the absorption-desorption characteristics of building materials and office papers, alongside airflow dynamics throughout the structure. Findings indicated predominant wintertime condensation, particularly in non-air-conditioned central sections such as the top floor. Tronchin et al. (2023) delved into the risk of interstitial condensation between interior walls and insulation within extant buildings across various European countries. They meticulously assessed water content in insulation (WCI) employing diverse materials, including natural fibers, mineral fibers, and synthetic alternatives. The study meticulously considered different climatic zones and scrutinized single-family dwellings constructed between 1945 and 1969. Simulations were conducted, taking into account the application scenario, the chosen stratigraphic composition, and the exposure of the existing building system. Findings indicated the occurrence of interstitial condensation, notably concerning mineral and natural insulation materials, particularly within the climatic contexts of Oslo and Brussels. The study by Küçüktopçu and Cemek (2021) utilized the finite element method to simulate temperature distributions within various wall constructions (solid brick, Ytong, concrete) in poultry facilities across diverse climatic zones within Türkiye. The research spanned cities with distinct climatic profiles, including Antalya, Samsun, Ankara, and Erzurum. Their findings highlighted a higher incidence of latent condensation in Ankara and Erzurum, characterized by lower outdoor temperatures (-0.50 and 6.30 ºC) compared to the other cities. Consequently, they recommended the installation of vapor barrier materials on the warm side of walls to mitigate latent condensation risks. Unal (2019) analyzed condensation and vapor diffusion resulting from differently positioned insulation within walls in Mardin province, Türkiye. By constructing six distinct wall models with uniform insulation thickness of 20 cm, evaporation and condensation levels were quantified, with 2 cm of interior plaster and 3 cm on the exterior applied to unreinforced concrete walls. Results indicated that the worst-performing wall structure in terms of condensation and evaporation occurred in the insulated wall's central position, followed by the inner position. Notably, no condensation was observed on externally insulated walls. Hatipoğlu et al. (2022) modeled various compound wall configurations for Yalova city, Türkiye, utilizing the TS 825 computer program. Condensation analyses were conducted between each wall layer for every wall type, identifying critical temperatures. They observed condensation within walls with insufficient insulation and delineated specific requirements for each wall type to forestall condensation. Çağman and Enver (2023) investigated condensation levels between layers of the three most prevalent wall types in Kütahya city, Türkiye. Employing the Glaser Diagram Method and considering climate data, they quantified condensation amounts. Wall 3 exhibited condensation levels of 0.001696833 kg/m2.h at 0ºC and 0.002142743 kg/m2.h at -21ºC, attributed to low outdoor temperatures. In comparison to previous work that focused largely on minimizing insulation thickness for efficiency in the usage of energy or overall condensation danger, the current work directly analyzes the role of insulation thickness on the occurrence of condensation within a cold climate area (Sivas, Türkiye). The unique climatic properties of Sivas, with extreme temperatures and higher winter humidity, require that the accumulation of moisture in insulated structures be better examined. While earlier works have focused on the occurrence of risks due to condensation in various climates, the gap in research on locations that have severe winters and wide indoor-outdoor temperature gradients, where high levels of condensation danger, exists. This work fills that gap by assessing the required thickness of insulation with varying indoor and outdoor humidities, setting thresholds for saturation, and making a long-term analysis on the insulation. The findings of the work assist in the development of efficient insulation techniques for cold climates that ensure both thermal efficiency and control over dampness, which are important towards the sustainability and durability of building infrastructure. The main aim in this paper, dealing with the detailed analysis of the problem, is to drastically reduce the losses of heat as well as the amount of water vapour that would be transferred by applying the principles of saturation pressure and the partial pressure of water vapour, precisely at the temperature inherent in each given specific layer of the building material. Further in the paper, attention is paid to a given wall of the building, which is supposed to involve applications of internal and external insulation in radically reducing the possible risk of condensation. The minimum thickness of insulation is duly calculated. This is critical to the cautious design of the whole wall system and ensuring it will be effective in maintaining the integrity of the thermal structure and preventing possible moisture problems. Thickness of thermal insulation plays an important role in building and efficiency in buildings, considering that moisture can enhance the rate of heat transfer in highly moistened regions, especially in cold climate conditions. This directly impinges on the comfort of the indoor environment and heating costs in the general energy consumption needed to create a livable atmosphere. Thus, the specific city selected for this examination is Sivas, which is within the 4th degree day zone in Türkiye (Kan, 2022). The winters are really cold and often come with substantial snowfall.

2. Materials and Methods

2.1. Heat Conduction and Water Vapor Diffusion of Wall Structure

The current study was conducted in Sivas, Türkiye, which has a continental climate that is exemplified by cold, snowy winters and warm summers. The climatic conditions of Sivas are suitable to induce condensation, and hence the area is appropriate to study the implications of insulation thickness on condensation levels. This research is focused on the link between insulation thickness and condensation occurrence within walls, with emphasis on Sivas, Türkiye's cold climate. The wall assembly in question has several building materials, with internal and external insulation layers. An analysis of heat transfer and water vapor diffusion through mathematical models and simulations was undertaken to determine the level of insulation thickness to prevent condensation.

Figure 1 shows the type of externally and internally insulated walls consisting of different building materials. Since Sivas is in a cold climate region and the outdoor temperature drops considerably at night, a wall with thermal insulation from both the inside and outside is designed. The water vapor resistance of Expanded Polystyrene (EPS) can vary in a wide range depending on its density (μ = 20-100) (Anonymous, n.d.). The water vapor resistance of the thermal insulation material should be low in external insulation applications and high in internal insulation applications (Bademlioğlu et al., 2018). Since the vapor resistance of EPS can vary within desired ranges, it offers suitable options for both external and internal thermal insulation applications. Vapor barriers are used to control the movement of water vapor between building elements. Vapor barriers are used to prevent indoor moisture from reaching insulation materials and damaging them (Lstiburek and Eng (2004). Especially in cold climates, vapor barriers are used to prevent the hot and humid indoor air from coming into contact with the cold air outside. This way, the risk of condensation and moisture damage is reduced (Anonymous, n.d.). Fiber cement is a material that is resistant to decay, cracking and insect damage. These features provide long-lasting and maintenance-free wall covering (Gudayu et al., 2025). Fiber cement is resistant to moisture and water, providing a coating that is not affected by moisture indoors and outdoors (Gorzelanczyk and Schabowicz, 2014). In this study, a number of equations were used in accordance with the literature to perform the analysis (Kaynaklı et al., 2018; Yamankaradeniz, 2015).

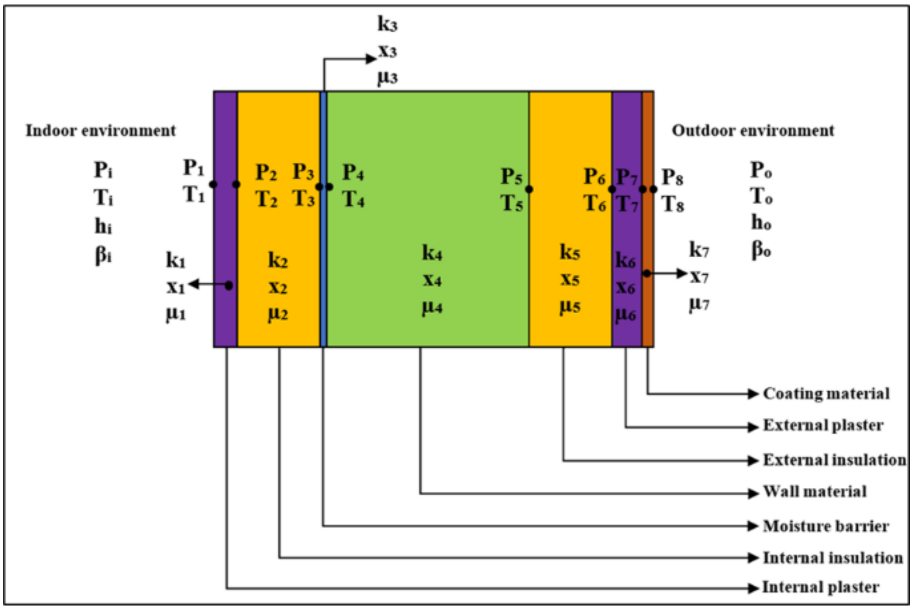

Figure 1. Schematic presentation the wall with internal and external insulation.

Heat flux in steady-state for indoor and outdoor environments (equations 1 and 2):

$$q = h_i(T_i - T_1) \tag{1}$$
$$q = h_o(T_n - T_o) \tag{2}$$

Heat flux in steady-state for building material layers (equation 3):

$$q = \frac{k_n}{x_n}(T_n - T_{n+1}) \tag{3}$$

Total heat flux for all wall composition in steady-state (equation 4):

$$q = \frac{T_i - T_o}{\frac{1}{h_i} + \sum \frac{x_n}{k_n} + \frac{1}{h_o}} \tag{4}$$

Similar to heat conduction, the vapor vapour diffision in the indoor and outdoor environments in a wall composition (equations 5 and 6):

$$w = \beta_i(P_i - P_1) \tag{5}$$
$$w = \beta_o(P_n - P_o) \tag{6}$$

The vapor vapour diffusion in steady-state for building material layers (equation 7):

$$w = \frac{\mu_{p_n}}{x_n}(P_n - P_{n+1}) \tag{7}$$

The vapor vapour diffision for the all wall composition (equation 8):

$$w = \frac{(P_i - P_o)}{\left(\frac{1}{\beta_i} + 1.5 \times 10^3 \left(\sum \frac{x_n}{\mu_{p_n}}\right) + \frac{1}{\beta_o}\right)} \tag{8}$$

Indoor and outdoor water vapor partial pressure (equations 9 and 10):

$$P_i = \theta_i P_{s,i} \tag{9}$$
$$P_o = \theta_o P_{s,o} \tag{10}$$

Vapor permeability resistance (equations 11 and 12):

$$\delta = \frac{1}{\mu_p} \tag{11}$$
$$\delta = \mu \delta_{air} \tag{12}$$

Rearranging equation 13, the vapor vapour diffusion for the all wall composition:

$$w = \frac{(P_i - P_o)}{\left(\frac{1}{\beta_i} + 1.5 \times 10^3 (\sum x_n k_n) + \frac{1}{\beta_o}\right)} \tag{13}$$

Within the scope of this study conducted for a building within the borders of Bitlis province, data on environmental conditions and other parameters in order to calculate the insulation thickness required to prevent condensation on a wall with a determined structure are given in Table 1 (Kaynaklı et al., 2018; Yamankaradeniz, 2015).

3. Results and Discussion

Figure 2 depicts the requisite thermal insulation thicknesses necessary to forestall condensation, contingent upon fluctuations in outdoor temperature. As outdoor temperatures ascend from -20 to -2°C, the requisite thermal insulation thickness also rises for indoor temperatures of 23, 21, and 19°C. Upon reaching specific thresholds (IT=19°C-OT=-5°C, IT=21°C-OT=-4°C, and IT=23°C-OT=-3°C), thermal insulation becomes unnecessary as condensation ceases to occur. However, the differential pressure between the water vapor inside and that outside becomes increasingly large at lower temperatures, hence raising the possibility of condensation on the walls of buildings to appreciable levels. Thus, with decreasing outdoor temperatures, the anticipated increased thickness of thermal insulation for buildings brings out the crucial importance of artful selection of building materials and architectural designs compatible with prevailing outdoor conditions.

Table 1. Parameters and values used in calculations

Parameter	Value
Building insulation material	EPS
Building wall structure	Vertical Perforated Brick
Building coating material	Fiber cement board
Building vapor barrier	Polyethylene
Indoor temperature	19°C, 21°C and 23°C with a default value of -21°C
Outdoor temperature	-20°C to -2°C with a default value of -15°C
Indoor relative humidity	30% to 65% with a default value of 50%
Outdoor relative humidity	50% to 80% with a default value of 70%
Indoor convection heat transfer coefficient	8.3 W/(m²K)
Outdoor convection heat transfer coefficient	34 W/(m²K)
Thermal conductivity of insulation material	0.040 W/m K
Thermal conductivity of wall structure	0.17 W/m K
Thermal conductivity of coating material	0.20 W/m K
Thermal conductivity of moisture barrier	0.03 W/m K
Thermal conductivity of internal plaster	0.87 W/m K
Thermal conductivity of external plaster	1.40 W/m K
Thickness of wall structure	0.19 m
Thickness of coating material	0.02 m
Thickness of vapor barrier	0.003 m
Thickness of internal plaster	0.02 m
Thickness of external plaster	0.03 m
Resistance factor of internal plaster	10
Resistance factor of external plaster	16.5
Resistance factor of insulation material (left)	100
Resistance factor of vapor barrier	250
Resistance factor of coating material	30
Resistance factor of insulation material (right)	20
Resistance factor of wall material	10

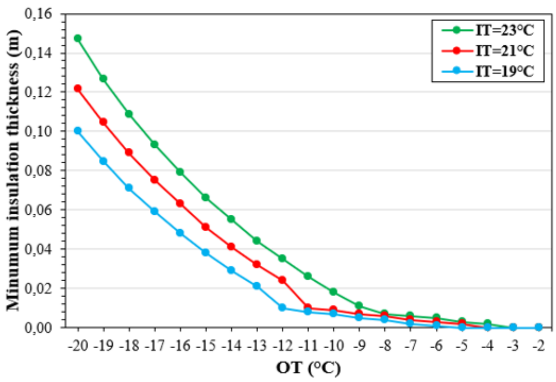

Figure 2. Alteration of required minimum insulation thickness with outside temperature (φ_i=0.5,φ_o=0.7).

Figure 3 shows the dependencies of water vapor flow rates, required to prevent the condensation, by the variation of outdoor temperature with respect to the minimum necessary insulation thickness. It is about this graph being specifically relative to the way how these flow rates are changing in case of variation in outdoor temperature, due to the minimum thickness of the insulation in which this avoidance is reached. And this is known intuitively that when the temperature outside increases, the heat transfer rates, as well as the mass exchange rates, of course, start to decrease. And this tendency and its proper development are, in fact, determined by one important factor, which is the lesser thickness of the thermal insulation layer, with respect to this dynamics. Accordingly, it gives a high number of water vapor transferred from indoors to outdoors. Nevertheless when it attains critical values given by (IT=19°C-OT=-5°C, IT=21°C-OT=-4°C and IT=23°C-OT=-3°C) in which insulation becomes ineffective, then further rises in the outdoor temperature increases the partial pressure of the external atmosphere and hence fall in the water vapor transmission rates.

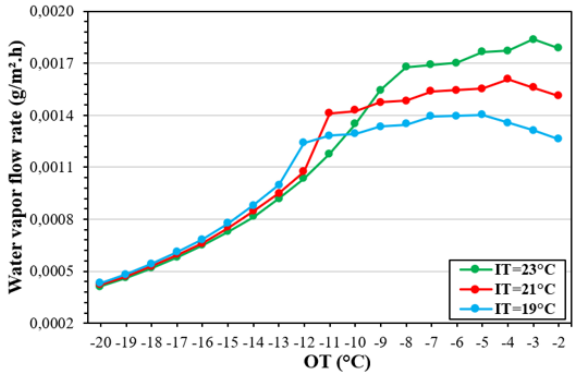

Figure 3. Alteration of water vapor flow rate with outside temperature based on required minimum insulation thickness ($\varphi_i = 0.5, \varphi_o = 0.7$).

Figure 4 is a detailed representation that shows the relationship between the minimum insulation thickness that will prevent condensation with indoor relative humidity levels and also the minimum required thickness of insulation. It can be observed that as the increase in outdoor relative humidity increases from the level of 30% to a higher percentage of 65%, the thickness requirement of thermal insulation also rises correspondingly. When the percentages of relative humidity are at 70% outdoors, the insulation thickness requirements increase from 0.004 meters to 0.090 meters; for relative humidity of 60%, the insulation thickness increases from 0.003 meters to 0.060 meters; and for 50% relative humidity, it develops from 0.002 meters to 0.043 meters. Under the condition of a small internal relative humidity of about 30%, the thickness of thermal insulation will be close to zero since condensation is avoided. However, a higher indoors relative humidity increases the transport of water vapor from indoors to outdoors, which can cause wall condensation and structural damage. To preempt this scenario, insulation thickness must be increased, as thicker insulation limits the passage of warm and moist indoor air outdoors, reducing the likelihood of wall condensation. This underscores the necessity of adjusting insulation thickness to mitigate condensation risks in response to external humidity levels, thereby optimizing energy efficiency, enhancing interior comfort, and nsuring the long-term integrity and performance of the structure.

Figure 5 depicts the various water vapour flow variations, the effect of which needs to be handled properly to avoid any resulting condensation. This variation has been plotted with the changes in indoor relative humidity-a very important factor since once again its value is dependent upon the required minimum thickness of the insulation that is required to be applied. The number of water vapours that diffuse into the wall structure will increase proportionately as the indoor relative humidity increases. Nevertheless, beyond a specific threshold (IRH=35% for ORH=70%, IRH=35% for ORH=60%, and IRH=45% for ORH=50%), condensation takes place, resulting in a reduction in the volume of water vapor that permeates due to the thermal insulation implemented on the wall. Furthermore, as the relative humidity in the external environment escalates, there is a corresponding increase in the necessary thickness of insulation to mitigate the potential for condensation. For this reason, the larger the relative humidity of the outside environment, the smaller is the amount of water vapor transferred from the indoors to the outdoors.

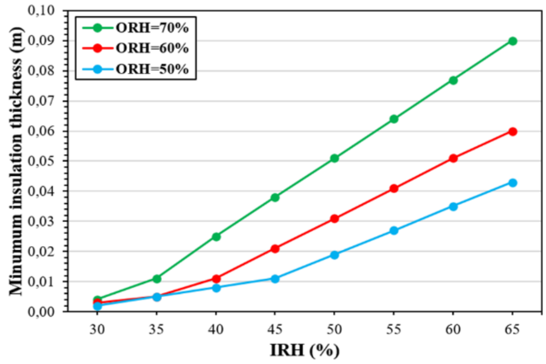

Figure 4. Alteration of required minimum insulation thickness with indoor relative humidity ($T_i = 21°C, T_o = -15°C$).

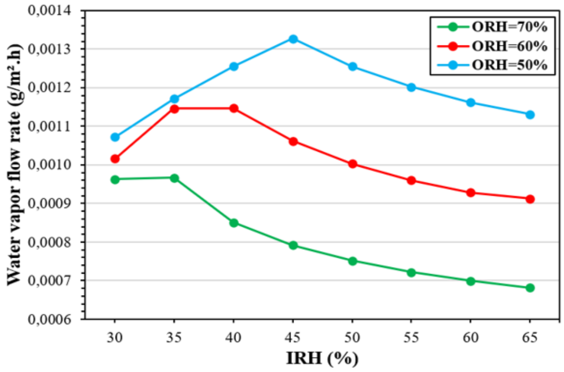

Figure 5. Alteration of water vapor flow rate with indoor relative humidity ($T_i = 21°C, T_o = -15°C$).

Figure 6 shows the minimum insulation thickness required to avoid condensation with variable outdoor relative humidity, organized by the minimum insulation thickness. The minimum thermal insulation thickness necessary to avoid condensation for indoor relative humidity values of 70%, 60%, and 50% increases when the outdoor relative humidity also increases within a range of 0.019 to 0.091 meters, 0.035 to 0.129 meters, and 0.050 to 0.017 meters, respectively. In cases where the outside relative humidity increases from 50 to 80%, the partial pressure of the water vapor in the external atmosphere increases and, hence, reduces the water vapour permeation, thus lowering the condensation risks. However, high rise in outdoor relative humidity limits the capacity of outdoor air for water vapour absorption, which raises the probability of condensation on wall layers. Besides, higher indoor relative humidity may provide higher indoor-to-outdoor water vapour movement, higher thickness of thermal insulation being required in order to avoid probable condensation.

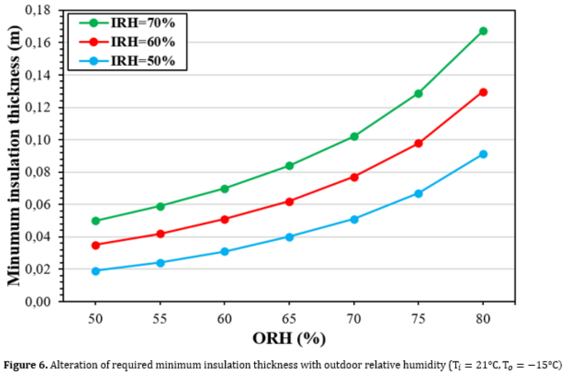

Figure 6. Aleration of required minimum insulation thicknes with outdoor relative humidity. $\mathrm{T}_i = 21°\mathrm{C}, \mathrm{T}_o = -15°\mathrm{C}$).

Figure 7 shows the variation of the water vapor flow rate to prevent condensation depending on alterations in outdoor relative humidity based on required minimum insulation thickness. It could be seen that in the case of indoor relative humidity values of 70%, 60%, and 50%, water vapor flow rate decreases as outdoor relative humidity increases from 0.00118 to 0.000447 g/m^2.h, from 0.00116 to 0.00047 g/m^2.h, and from 0.00125 to 0.0005 g/m^2.h, respectively. Then, the effect of the increase in thickness of insulation becomes more dramatic, and the water vapor flow rate decreases much more significantly. Also, the indoor relative humidity reaches 70%, when the volume of transferred water vapor decreases much more significantly due to a more substantial thermal insulation effect. The latter reduction is around 11-14% for outdoor relative humidity of 50-65% and 15-24% for outdoor relative humidity of 70-80%.

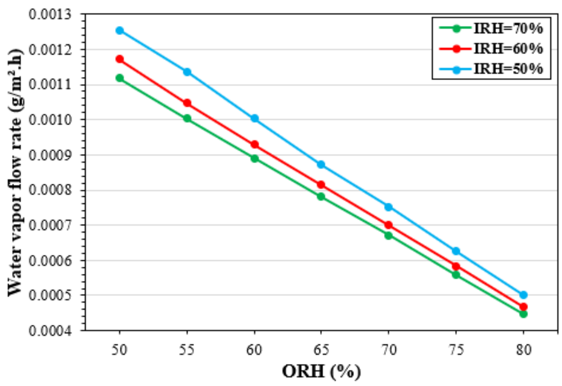

Figure 7. Alteration of water vapor flow rate with outdoor relative humidity ($\mathrm{T}_i = 21°\mathrm{C}, \mathrm{T}_o = -15°\mathrm{C}$).

4. Conclusion

The current study examined the impact of insulation thickness on the formation of condensation in buildings located in Sivas, Türkiye, a region that is characterized by cold climatic conditions. The durability of the insulating material, Expanded Polystyrene (EPS), under scrutiny in this research is affected by several factors that include humidity, ultraviolet radiation, mechanical stress, and temperature cycles. In perfect conditions, the life span of the EPS insulation could be more than 30 to 50 years with little degradation. Nevertheless, continuous contact with water and environmental pollutants could make the insulation lose its thermal efficiency through the change in the density and the vapor permeable properties of the material. The success of degradation of the insulation coating depends on its ability to resist moisture absorption and surface degradation. This study used fiber cement boards as an external protection layer, which significantly improves insulation stability by protecting EPS from direct contact with environmental factors. Over time, the insulation performance can reduce by approximately 5-10% over a twenty-year period due to material aging, water retention, and microstructure changes. To prevent long-term degradation, it is necessary to maintain proper vapor barriers and protective coatings, and thus maintain the continued performance of thermal insulation with minimal performance loss over the building's life.

Results from the study established that insulation thickness is central to reducing condensation and maintaining thermal efficiency, especially in environments where there is much variation in temperature and humidity. The findings showed that the increase in the critical factor of condensation due to high indoor humidity levels, lower outdoor temperatures, and higher external humidity increases the potential for the occurrence of condensation. In order to avert this condition, it becomes necessary to use thicker layers of insulation, particularly when indoor relative humidity is above 70%. On the other hand, when the critical factor of condensation is decreased due to lower indoor humidity, higher outdoor temperatures, or better diffusion properties of building materials, the need for thick insulation is less. In these cases, the risk level pertaining to condensation occurrence is low with thinner insulation thickness. Additionally, the study established a saturation thickness, after which additional insulation does not significantly reduce condensation hazards. The study revealed that in moderate conditions, insulation thickness of 4 to 6 cm was sufficient, whereas in cases of high humidity (≥70%), the required insulation was 8 to 10 cm. In cases where external humidity was more than 80%, insulation thickness of more than 10 cm provided decreasing benefits in relation to the prevention of condensation. The study found that a significant reduction in condensation, as compared to the required thickness of insulation, occurs at an external relative humidity of around 70%. At lower humidity levels, the risk of condensation reduces significantly, leading to the need for thinner insulation. However, at external humidity levels above 70%, there is a greater need for thicker insulation to prevent the buildup of moisture in wall assemblies. At external relative humidity levels above 80%, further increases in thickness above 10 cm provide decreasing returns, indicating a point of saturation where further increases in thickness provide little benefit in condensation reduction. This implies that insulation selection needs to be optimized on the basis of both thermal efficiency and moisture management, thus providing energy conservation while preventing possible structural damage due to moisture accumulation. In conclusion, this study highlights the importance of creating insulation systems with specific climatic conditions in mind. By considering factors like indoor and outdoor humidity, temperature variations, and material properties, one can determine the most appropriate thickness of insulation that has a minimal risk of condensation, increases indoor comfort, and improves the energy efficiency of buildings. Future studies can focus on the transient dynamics of heat and moisture transport and the durability of materials under different climatic conditions to further develop insulation optimization techniques.

Author Contributions

The percentages of the authors' contributions are presented below. All author reviewed and approved the final version of the manuscript.

	C.A.	M.T.Ç.
C	100	
D	100	
S		100
DCP	50	50
DAI	100	
L	100	
W	100	
CR	50	50
SR	100	50

C=Concept, D=design, S=supervision, DCP=data collection and/or processing, DAI=data analysis and/or interpretation, L=literature search, W=writing, CR=critical review, SR=submission and revision.

Conflict of Interest

The authors declare that they have no conflict of interest in this study.

Ethical Approval Statement

Since this study did not involve any studies on animals or humans, ethics committee approval was not obtained.

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