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THE EFFECT OF WATER VAPOR DIFFUSION RESISTANCE FACTOR OF INSULATION MATERIALS FOR OUTER WALLS ON CONDENSATION

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Abstract: Condensation, which is the result of water vapor diffusion, affects the heat transfer in the building material negatively. The condensation which is seen mostly in winter seasons at building materials, occurs when the surface temperature of the building material in contact with air falls below the raw temperature of the air. In this case, condensed water may cause mildew, fungal growth, odors, and deterioration of dye and building materials or adversely affected thermal insulation on the walls. Materials used for thermal insulation in buildings constitute resistance against water vapor diffusion. Water vapor diffusion resistance factor (VDRF) of materials can vary over a wide range. In this study, considering VDRF range that is commonly encountered in insulation applications, the effect of VDRF of insulation materials on condensation within constructions, and on the minimum thickness of insulation required to prevent this condensation accordingly were examined. Externally insulated wall was taken as sample wall model, heat and mass transfer calculations from wall unit area and insulation thickness minimization were performed for different indoor-outdoor temperatures and relative humidity values. As a result of the analysis conducted, in constant indoor-outdoor conditions in general, as VDRF increases, the risk of condensation inside the wall first decreases and then increases. Minimum insulation thickness that is required to be applied to prevent condensation also shows a similar trend depending on the VDRF. For constant VDRF, it was come to the conclusion that as the difference between indoor-outdoor temperatures and relative humidity increases, the risk of condensation and consequently required insulation thickness increases.
Keywords: Water vapor diffusion resistance factor, Condensation, Insulation, Thermal conductivity.

DIŞ DUVARLAR İÇİN YALITIM MALZEMESİ SU BUHARI DİFÜZYON DİRENCİNİN YOĞUŞMAYA OLAN ETKİSİ

Özet: Su buharı difüzyonu sonucu oluşan yoğuşma, yapı malzemelerindeki ısı transferini olumsuz yönde etkiler. Yapı malzemelerinde genellikle kış mevsiminde görülen yoğuşma, hava ile temas eden yapı malzemesi yüzey sıcaklığının havanın çiy noktası sıcaklığının altına düşmesiyle gerçekleşir. Bu durumda yoğuşan su duvarlarda küf, mantar üremesi, koku, boya ve yapı malzemesi bozulmalarına veya ısı yalıtımın olumsuz etkilenmesine neden olabilir. Binalarda ısı yalıtımı için kullanılan malzemeler, su buharının difüzyonuna karşı direnç (VDRF) oluşturmaktadır. Malzemelerin VDRF geniş bir aralıkta değişkenlik gösterebilmektedir. Bu çalışmada yalıtım uygulamalarında sıklıkla karşılaşılan su buharı difüzyon direnç aralığı dikkate alınarak, yalıtım malzemesi VDRF'nin yapı içindeki yoğuşmaya ve buna bağlı olarak yoğuşmanın önlenmesi için gerekli minimum yalıtım kalınlığına olan etkisi incelenmiştir. Örnek duvar modeli olarak dıştan yalıtımlı duvar tipi ele alınmış, farklı iç-dış ortam sıcaklık ve bağıl nem değerleri için duvarın birim alanından olan ısı-kütle transferi hesaplamaları ve yalıtım kalınlığı minimizasyonu yapılmıştır. Yapılan analiz sonucunda, genel olarak sabit iç-dış ortam koşullarında, yalıtım malzemesi su buharı difüzyon direnci arttıkça duvar içindeki yoğuşma riski önce azalmakta sonra artmaktadır. Yoğuşmanın gerçekleşmemesi için uygulanması gerekli minimim yalıtım kalınlığı da buna benzer bir eğilim göstermektedir. Sabit VDRF için ise, iç-dış ortam arasındaki sıcaklık ve bağıl nem farkı arttıkça, yoğuşma riski ve buna bağlı olarak gerekli yalıtım kalınlığının arttığı sonucuna varılmıştır.
Anahtar Kelimeler: Su buharı difüzyon direnç faktörü, Yoğuşma, Yalıtım, Isı iletim katsayısı

NOMENCLATURE

h	Convective heat transfer coefficient [$W/m^2{}^\circ C$]
k	Thermal conductivity [W/m°C]
P	Water vapor partial pressure [kPa]
q	Heat flux [W/m^2]
R_w	Thermal resistance of the wall without the insulation [m^2 °C/W]
T	Temperature [°C]
w	Water vapor flow rate [kg/h m^2]
x	Thickness of the construction material [m]

Greek Symbols

θ	Relative humidity [%]
μ	Water vapor diffusion resistance factor of material
μ_p	Vapor permeability of building material [kg/h m kPa]
δ	Vapor permeability resistance of building material [kPa m h/kg]
δ_{air}	Vapor permeability resistance of air [kPa m h/kg]
β	Vapor permeability coefficient [kg/m^2h kPa]

Subscripts

i	Indoor
ins	Insulation
n	Number of wall layers
o	Outdoor
s	Saturation

INTRODUCTION

When a system contains two or more species (components) whose concentration varying from point to point, there is a natural tendency for mass to be transferred to minimize the concentration difference within the system. The transport of one component from a region of higher concentration to that of lower concentration is called mass transfer. In the outer building walls, water vapor transmission is generally from indoor environment to outdoor environment. Variable temperature and relative humidity conditions in indoor and outdoor environment cause vapor transition within the construction element by affecting the water vapor pressure difference. When the partial pressure of water vapor in the building material becomes equal to water vapor saturation pressure at any point in the inner layers, condensation occurs (Ertas, 2001). Condensation formed in building materials leads to undesirable results such as damage of materials, reduction in resistance and increase in heat transfer.

In order to prevent condensation, resistance of the building component against water vapor movement should be increased in general. The simplest and the most basic way for this is to apply insulation and to increase the insulation thickness. During insulation process, thermodynamically the most suitable insulation material should be preferred and an insulation thickness capable of preventing condensation should be applied. In selection of insulation material, the water vapor diffusion resistance of the material plays an important role in terms of minimum insulation thickness required to minimize the risk of condensation. In general, vapor diffusion resistance refers to the resistance of a material to a certain amount of water passing through the unit surface in the unit time under certain temperatures, dampness and thickness. In literature, in addition to the concept of vapor diffusion resistance, vapor diffusion resistance factor (VDRF) is more widely used in practice. VDRF is defined as the ratio of the resistance shown by a material with the unit thickness against passage of water vapor to the resistance shown by the equivalent thickness of air against passage of water vapor (Schroeder, 2016; Mukhopadhyaya and Kumaran, 2007).

Effects of insulation materials with different VDRFs on condensation are different and required minimum insulation thickness varies accordingly. VDRF of materials can vary over a wide range. Insulation materials used in the outer building wall insulation applications and some of their characteristics are shown in Table 1.

Quite a few studies in literature consider condensation for calculation of optimum insulation thickness. Arslan and Kose (2006) examined thermodynamic optimization of insulation thickness, considering condensation for Kütahya province. Heperkan et al. (2001) developed a computer program facilitating vapor diffusion and condensation calculations and detecting the point where condensation occurs in building material.

Table 1. Insulation materials and some thermodynamic properties (TS 825, 2008)

Insulation Material	Thermal Conductivity, *k* (W/m°C)	Water Vapor Diffusion Resistance Factor, *μ* (-)
Glass Wool	0.035 - 0.050	1
Stone Wool	0.035 - 0.050	1
EPS	0.035 - 0.040	20 - 100
XPS	0.030 - 0.040	80 - 250
Rigid Polyurethane Foam	0.025 - 0.040	30 - 100
Phenolic Foam	0.030 - 0.045	10 - 50
Cork Sheet	0.045 - 0.055	5 - 10
Expanded Perlite Sheet	0.045 - 0.065	5
Wood Fiber Sheet	0.035 - 0.070	5

Atmaca and Kargici (2006) examined vapor transfer and condensation phenomenon in a building (which is insulated internally and externally) in the province of Konya. Ucar (2010) calculated optimum insulation thickness by using exergy analysis at various indoor temperatures (18°C, 20°C and 22°C) for four provinces located in different climate zones (Antalya, Istanbul, Elazig and Erzurum) in Turkey. She determined energy savings obtained with optimum insulation application. In the exergoeconomic analysis, the condensed amount of water within the building material was taken into consideration.

Chang and Kim (2015) investigated the heat and moisture performance of two different wall structures mainly used in Korea using simulation program. In this study, the water content of the various building materials, hygrothermal behavior of the wall structure, condensation risk and mould growth potential were identified to design comfort building environment. Liu et al. (2015) investigated the effect of humidity transfer on the thermal performance of buildings envelopes in the HSCW (hot summer cold winter) zone of China. In this study, a coupled heat and humidity transfer model is developed to calculate conduction loads through buildings envelopes. Moon et al. (2014) examined the effect of moisture transport on overall building performance, such as energy efficiency, thermal comfort, and mould growth risks in built environments based on hygrothermal simulation. Liu et al. (2015) a designed the coupled heat and moisture transfer model which considers the effect of the moisture transfer on heat transfer to estimate the cooling and heating transmission load. In addition, the insulation thickness is optimized by using a lifecycle total cost analysis with the P_1-P_2 economic model.

You et al. (2017) investigated the transient property of moisture condensation on the internal surface of buildings in high humidity climate and aim to determine the typical places where moisture condensation often occurs. Latif et al. (2014) compared the hygrothermal performance of hemp and stone wool insulations in vapor open timber frame wall panels in operating conditions, incorporating moderate and high interior relative humidity. Kaynakli et al. (2018) optimized the thermal insulation thickness used in the outer walls of buildings composing of different insulation applications having the same thermal resistance by considering condensation. Vasilyev et al. (2016) presented the outcomes of the numerical study aimed at building a model of the condensation processes that occur due to a flow of moist air when the air was cooled and heat was utilized. However, in all of these studies, water vapor diffusion resistance factor of insulation materials was taken as a constant and its effect on condensation was not examined.

In this study, the effect of VDRF of insulation materials for externally insulated outer wall applications on condensation and the minimum thickness of insulation material required to prevent condensation within the wall building material were examined. Heat and mass transfer calculations from unit wall area and insulation thickness minimizations were performed for different indoor-outdoor conditions (relative humidity and temperature). The study also investigated the relationship between the thermal conductivity and VDRF of insulation material, and the obtained values were given in graphics.

MATERIALS AND METHODS

Heat Transfer and Water Vapor Diffusion in Composite Plane Walls

In Figure 1, an externally insulated wall application is shown. In applications, indoor convective heat transfer coefficient h_i, outdoor convective heat transfer coefficient h_0, thermal conductivity of the materials k and their thickness x are given so that steady state heat flux can be written as:

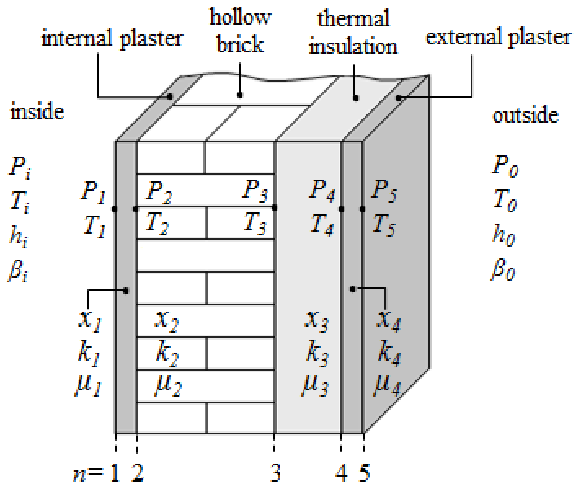

Figure 1. Externally insulated wall application

$$q = h_i(T_i - T_1) \Rightarrow T_1 = T_i - q/h_i \quad (1)$$

$$q = \frac{k_n}{x_n}(T_n - T_{n+1}) \Rightarrow T_{n+1} = T_n - q/\left(\frac{k_n}{x_n}\right) \quad (2)$$

While Eq. (1) is used for indoor and outdoor calculations, Eq. (2) is used for calculations for the layers of the building material. In a similar manner, heat flux is given as follows for the entire composite plane wall:

$$q = (T_i - T_o)/\left(\frac{1}{h_i} + \Sigma\frac{x_n}{k_n} + \frac{1}{h_d}\right) = (T_i - T_o)/\left(R_w + \frac{x_{ins}}{k_{ins}}\right) \quad (3)$$

Similar to the heat transfer, indoor vapor permeability coefficient β_i, outdoor vapor permeability coefficient β_o, vapor permeability of the building materials μ_p and their thickness x are given so that steady-state water vapor flow rate in the wall can be written as:

$$w = \beta_i(P_i - P_1) \Rightarrow P_1 = P_i - w/\beta_i \quad (4)$$

$$w = \frac{\mu_{pn}}{x_n}(P_n - P_{n+1}) \Rightarrow P_{n+1} = P_n - w/\left(\frac{\mu_{pn}}{x_n}\right) \quad (5)$$

While Eq. (4) is used for indoor and outdoor calculations, Eq. (5) is used for calculations for the layers of the building material. Water vapor flow rate is given as follows for the entire composite plane wall:

$$w = (P_i - P_o)/\left(\frac{1}{\beta_i} + \sum \frac{x_n}{\mu_{p_n}} + \frac{1}{\beta_o}\right) \tag{6}$$

In Eq. (6), indoor water vapor partial pressure P_i, outdoor water vapor partial pressure P_o and their relationship between the indoor and outdoor relative humidity data is as follows:

$$P_i = \theta_i P_{s,i} \quad ; \quad P_o = \theta_o P_{s.o} \tag{7}$$

In Eq. (7), $P_{s,i}$ and $P_{s,o}$ are saturation water vapor pressures at indoor and outdoor temperatures, respectively. Vapor permeability resistance (δ) is used instead of the vapor permeability of the building materials (μ_p) given in Eq. (6) and vapor permeability resistance is defined as follows:

$$\delta = 1/\mu_p \tag{8}$$

Vapor permeability resistance (δ) is given in terms of the water vapor diffusion resistance factor of material (μ) and the vapor permeability resistance of air (δ_{air}) as follows:

$$\delta = \mu \delta_{air} \tag{9}$$

δ_{air} is generally taken as 1.5x10^3 kPa m h/kg (Arslan and Kose, 2006; Atmaca and Kargici, 2006). In addition, it is specified that this value can be used in water vapor diffusion processes within the range of -20 to +30 °C. After this approach, Eq. (6) can be written as follows:

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

The indoor vapor permeability coefficient can be taken as β_i = 0.111 kg/m^2 h kPa while the outdoor vapor permeability coefficient as β_o = 0.39 kg/m^2 h kPa.

Distribution of Temperature and Partial Pressure inside the Wall

For externally insulated wall applications, possible temperature and pressure distributions in the structure are shown schematically in Figure 2. The possible condensation point (4 plane lines) where partial and saturation pressures intersect (under typical indoor and outdoor environmental conditions) is shown in the figure. P_s pressure at each point shown in the figure is the saturation pressure of water vapor at that temperature. Temperature distribution on the plane wall is calculated from heat flux Eq. (1-3), and partial pressures are calculated using Eq. (4) and (10) for each point.

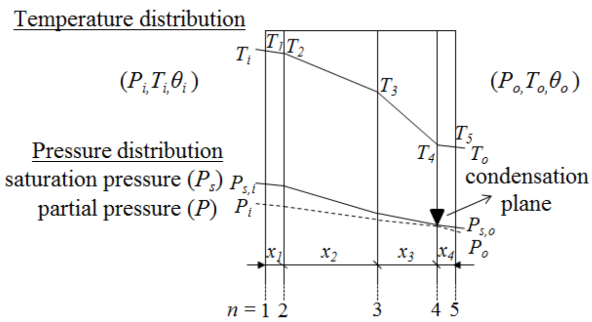

Figure 2. Possible temperature and pressure distribution in externally insulated wall application

Parameters and Assumptions

The constant and variables used in the study are shown in Table 2. In the analysis conducted for different VDRFs of insulation material, using the data shown in Table 2, heat and mass transfer passing through the unit area of externally insulated wall were calculated and then

Table 2. Data used in the study

Parameter	Value		
Indoor conditions			
Temperature, °C	22 to 26		
Relative humidity	50% to 70%		
Convective heat transfer coefficient, W/m^2 K	8.3 (Cengel and Ghajar, 2010)		
Vapor permeability coefficient, kg/m^2 h kPa	0.111 (Dagsoz, 1995)		
Outdoor conditions			
Temperature, °C	-7 to -3		
Relative humidity	70% to 90%		
Convective heat transfer coefficient, W/m^2 K	34 (Cengel and Ghajar, 2010)		
Vapor permeability coefficient, kg/m^2 h kPa	0.39 (Dagsoz, 1995)		
Wall structure	x (m)	k (W/m K) (Al-Sanea et al., 2005; Bolatturk, 2006)	μ (-) (Arslan and Kose, 2006 Kaynakli et al. 2018)
Externally Insulated Wall			
Internal plaster	0.02	0.87	10
Brick	0.2	0.45	6.8
Thermal insulation	x	0.030-0.040	20-250
External plaster	0.03	1.4	16.5

temperature and partial pressure distributions inside the wall were obtained. Partial pressure distributions vary depending on different VDRF values.

In order to simplify the analysis, following assumptions are made:

- The system is in the steady-state conditions.
- The thermophysical properties of the building materials (thermal conductivity, convective heat transfer coefficient) are assumed not to change depending on the temperature.
- One dimensional heat conduction occurs in the radial direction.
- There is no heat production in the system.
- Radiation exchange between the wall and surrounding is negligible.

RESULTS AND DISCUSSION

Partial pressure distributions at different VDRF of insulation material for a constant insulation thickness (x_{ins}=0.03 m) were given in Table 3, and they were compared to water vapor saturation pressures, a function of the obtained temperature distribution. In these analyses, indoor and outdoor conditions (temperature and relative humidity) were taken as 23°C, 60% and -6°C, 75%, respectively.

As seen in Table 3, as VDRF of insulation material increases, the amount of water vapor transmitting from indoor to outdoor environment decreases. Water vapor that cannot pass through insulation material accumulates in the inner surface of the insulation material and this situation causes increase in water vapor partial pressure at this layer (its 3 points). On the other hand, the amount of water vapor passing through the insulation material decreases and consequently a decrease is observed in the water vapor partial pressure on the outer surface (its 4 points) of the insulation material.

In Figure 3, partial and saturation pressure distributions in wall layers for different VDRFs are shown. In this figure, the risk of condensation on the wall can be seen more clearly and it is understood that condensation inside the wall changes place depending on the VDRF of insulation material. Condensation seen on the outer surface of insulation material can be seen on the inner surface of the insulation material above a certain VDRF.

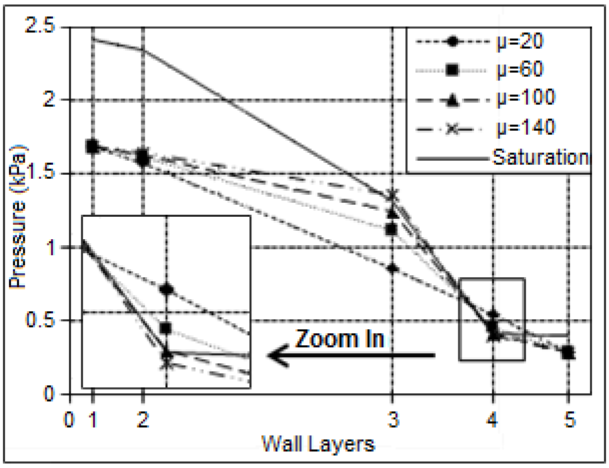

Figure 3. Water vapor partial and saturation pressure distribution in wall layers for different VDRFs of insulation material (for x_{ins}=0.03 m)

Effect of Water Vapor Diffusion Resistance Factor of the Insulation Material on Insulation Thickness in Different Indoor Conditions (Temperature and Humidity)

In different indoor relative humidity conditions (θ_i =50%, 60% and 70%), the effect of VDRF of the insulation material on minimum insulation thickness that is required to prevent condensation is shown in Figure 4. Here, indoor and outdoor temperatures were taken as 22°C and -3°C respectively, and outdoor relative humidity was determined as 70%. In general, depending on increase in VDRF of the insulation material, while the risk of condensation on the outer surface of insulation material decreases, the risk of condensation on the inner surface increases. For this reason, the insulation thickness in order to prevent condensation initially decreases and reaches a minimum value at a certain VDRF and then increases (Figure 4).

When indoor relative humidity increases, water vapor partial pressure difference increases between indoor with outdoor and consequently the amount of water vapor transferred from indoor to outdoor increases. This situation results in condensation on the outer surface of insulation material in low VDRF and on inner surface of insulation in high VDRF. Increase in the transfer of water vapor increases the partial pressure of water vapor inside the layers and the partial pressure intersects with the saturation pressure. For this reason, in order to prevent condensation, insulation thickness is increased and water vapor saturation pressure based on temperature inside the layers is ensured to be increased.

Table 3. Pressure distributions for different VDRF values (for x_{ins}=0.03 m)

VDRF of insulation material, μ	Amount of vapor passing through wall, w (g/m^2 h)	Saturation pressure (P_s) / Partial pressure (P)				
		1	2	3	4	5
20	0.3497	2.417 /1.681	2.349 /1.576	1.317 / 0.863	0.417 /0.548	0.403 / 0.289
60	0.2411	2.417 /1.682	2.349 /1.610	1.317 / 1.118	0.417 /0.467	0.403 / 0.288
100	0.1839	2.417 /1.683	2.349 /1.628	1.317 / 1.252	0.417 /0.425	0.403 / 0.288
140	0.1487	2.417 /1.683	2.349 /1.638	1.317 / 1.335	0.417 /0.398	0.403 / 0.288

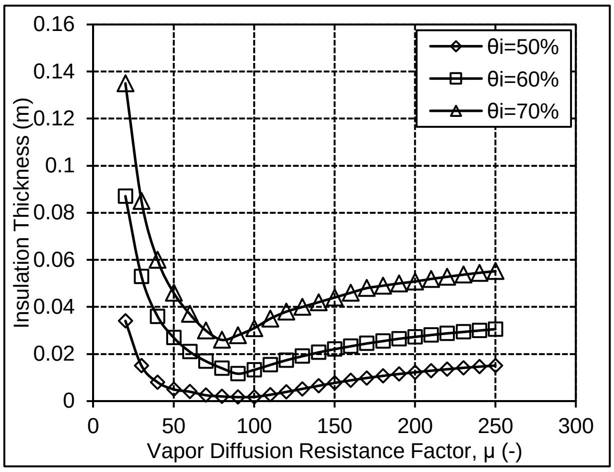

Figure 4. In different indoor relative humidity conditions, the effect of VDRF of the insulation material on insulation thickness that is required to prevent condensation (T_i =22°C, T_o=-3°C and θ_o =70%)

In different indoor temperature conditions (T_i =22°C, 24°C and 26°C), VDRF of the insulation material on minimum insulation thickness that is required to prevent condensation is shown in Figure 5. Here, indoor and outdoor relative humidity values were taken as 50% and 70% respectively, and outdoor temperature was determined as -3°C.

When indoor temperature increases, the difference between indoor and outdoor temperature and water vapor partial pressure increases. When the temperature difference increases, temperature inside the wall layers increases and consequently water vapor saturation pressure inside the layers also increases. This situation has a reducing effect on the risk of condensation. However, increase in the difference between indoor and outdoor water vapor partial pressure increases the risk of condensation. Because as the water vapor partial pressure difference increases, depending on indoor temperature, the amount of water vapor transmitting from indoor to outdoor increases. This situation results in increase in water vapor on the outer surface of insulation material in low VDRF and on inner surface of insulation in high VDRF. Increase in the water vapor increases the partial pressure of water vapor inside the layers and the partial pressure intersects with the saturation pressure. For this reason, water vapor saturation pressure inside the layers is ensured to be above partial pressure by increasing insulation thickness.

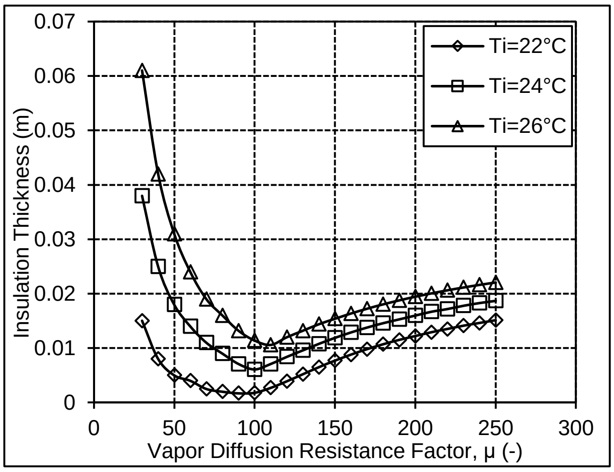

Figure 5. In different indoor temperature conditions, the effect of VDRF of the insulation material on insulation thickness that is required to prevent condensation (θ_i =50%, θ_o =70% and T_o =-3°C)

Effect of Water Vapor Diffusion Resistance Factor of the Insulation Material on Insulation Thickness in Different Outdoor Conditions (Temperature and Humidity)

In different outdoor relative humidity conditions (θ_o=70%, 80% and 90%), the effect of VDRF of the insulation material on insulation thickness that is required to prevent condensation is shown in Figure 6. Here, indoor and outdoor temperatures were taken as 22°C and -3°C respectively, and indoor relative humidity was determined as 50%.

When outdoor relative humidity increases, water vapor partial pressure difference decreases between indoor with outdoor and consequently the amount of water vapor transferred from indoor to outdoor decreases. However as outdoor relative humidity increases, water vapor partial pressure inside the wall increases and reaches saturation pressures. Therefore, for low VDRF, the risk of condensation on the outer surface of insulation increases. In order to prevent condensation, water vapor saturation pressure, based on temperature change inside layers, is increased by increasing insulation thickness. For high VDRF, it is seen that outdoor relative humidity does not have a significant effect on insulation thickness (Figure 6).

Figures 4 and 6 are analyzed together, it can be seen that when the difference between indoor and outdoor relative humidity increases, the VDRF providing minimum insulation thickness decreases. For this reason, under conditions in which high relative humidity difference, insulation material with lower VDRF should be used.

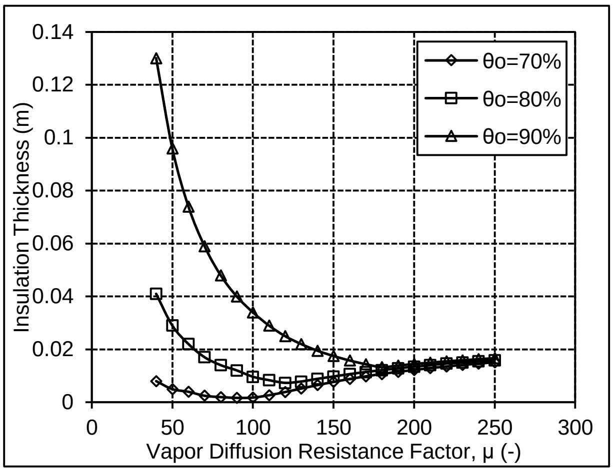

Figure 6. In different outdoor relative humidity conditions, the effect of VDRF of the insulation material on insulation thickness that is required to prevent condensation (T_i =22°C, θ_i =50% and T_o=-3°C)

In different outdoor temperature conditions (T_i =-3°C, -5°C and -7°C), the effect of VDRF of the insulation material on insulation thickness that is required to prevent condensation is shown in Figure 7. Here, indoor and outdoor relative humidity values were taken as 50% and 70% respectively, and indoor temperature was determined as 22°C.

When outdoor temperature increases, the difference between indoor and outdoor temperature and water vapor partial pressure decreases. The decrease in the temperature difference results in a decrease in the water vapor saturation pressures inside the wall layers. This situation has an increasing effect on the risk of condensation. However, as the difference in water vapor partial pressure decreases, the amount of water vapor transferred from indoor to outdoor also decreases. This situation results in decrease in the amount of water vapor on the outer surface of insulation material in low VDRF and on inner surface of insulation in high VDRF of the insulation material. Decreased amount of water vapor decreases water vapor partial pressure inside the layers and water vapor partial pressure value drops below saturation pressure value. For this reason, as outdoor temperature increases, the risk of condensation decreases and insulation thickness to prevent condensation decreases.

Figures 5 and 7 are examined together, it can be seen that when the difference between indoor and outdoor temperature increases, the VDRF providing minimum insulation thickness also increases. For this reason, under conditions in which a high temperature difference, insulation material with a higher VDRF should be used.

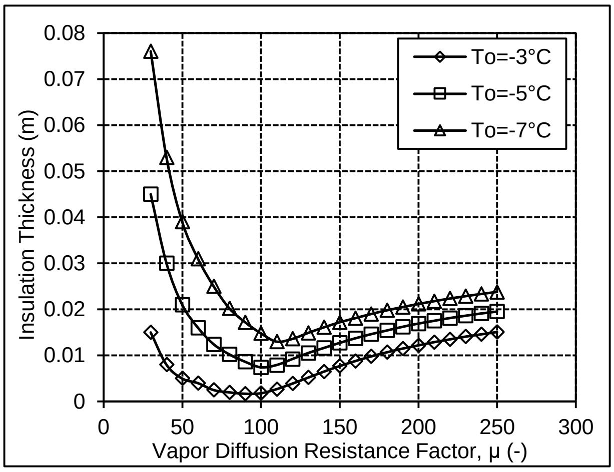

Figure 7. In different outdoor temperature conditions, the effect of VDRF of the insulation material on insulation thickness that is required to prevent condensation (T_i =22°C, θ_i =50% and θ_o=70%)

Relationship between Thermal Conductivity and Water Vapor Diffusion Resistance Factor of Insulation Material

Thermodynamic properties of insulation material affect condensation inside the building material. At different outdoor temperatures (T_o=-5°C and -3°C), the relationship between thermal conductivity and VDRF of insulation material for two different insulation thicknesses, is shown in Figure 8. As VDRF of insulation material increases, water vapor partial pressure on inner surface of the insulation increases and approaches saturation pressure, consequently the risk of condensation increases. For this reason, as VDRF of an insulation material for a constant insulation thickness increases, materials with lower thermal conductivity to prevent condensation should be used. Because as thermal conductivity of an insulation material increases, temperature on the inner surface of the insulation material and consequently water vapor saturation pressure decreases and this situation increases the risk of condensation much more. Similarly, when VDRF of an insulation material is lower, materials with higher thermal conductivity should be preferred.

Similarly, as the outdoor temperature decreases, the temperature difference between the indoor and outdoor increases and the risk of condensation increases. For this reason, it is more suitable to choose insulation materials with lower VDRF at lower outdoor temperatures in order to reduce the risk of condensation on the inner surface of the insulation.

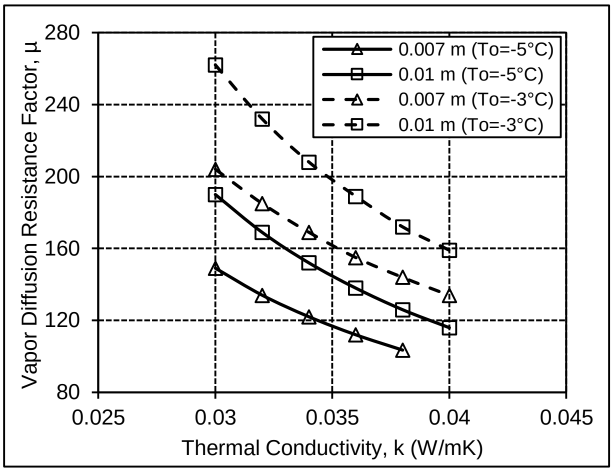

Figure 8. For constant insulation thicknesses (x_{ins}=0.007 and 0.01m), variation of VDRF of insulation material according to thermal conductivity (T_i =22°C, θ_i =50% and θ_o=70%)

For insulation materials with different thermal conductivities, variation of insulation thickness that is required to prevent condensation according to VDRF of insulation material is shown in Figure 9. It is seen in the figure that in low VDRF (up to μ=100), thermal conductivity of insulation material doesn't have a significant effect on insulation thickness but in high VDRF (from μ=100) the required insulation thickness increases with thermal conductivity.

As the thermal conductivity of the insulation material increases, while the temperature inside the layers down to inner surface of insulation material and consequently the water vapor saturation pressure decrease; the temperature and water vapor saturation pressure inside the layers beginning from the outer surface of the insulation increase. For this reason, while the risk of condensation seen on the outer surface of insulation decreases depending on the increase in thermal conductivity in low VDRF, the risk of condensation seen on the inner surface of insulation increases with thermal conductivity in high VDRF. In addition, as thermal conductivity of insulation material increases, a minimum insulation thickness can be obtained at lower VDRF (Figure 9).

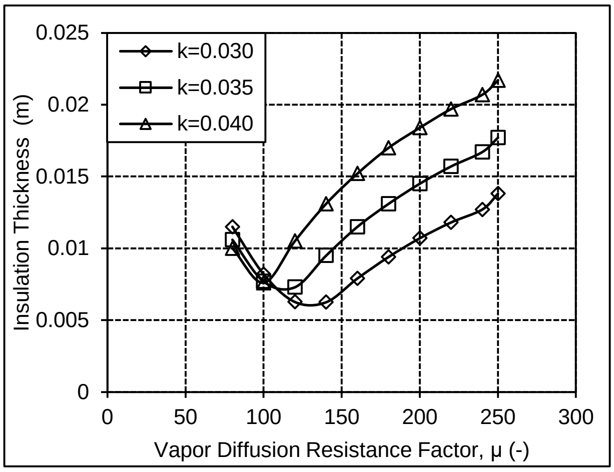

Figure 9. For insulation materials with different thermal conductivity, variation of insulation thickness that is required to prevent condensation according to VDRF of insulation material (T_i =22°C, θ_i =50%, T_o=-5°C and θ_o=70%)

CONCLUSION

In building insulation applications, water vapor diffusion resistance factor of insulation material is a determining factor in terms of condensation. For this reason, VDRF should be taken into consideration while selecting an insulation material. In this study, for externally insulated wall applications, the effect of VDRF of insulation material on condensation inside the structure and consequently on insulation thickness required to prevent condensation was examined. The results obtained in this study can be summarized as follows:

- When VDRF of an applied insulation material is low, it causes to increase the risk of condensation on the outer surface of insulation; and when it is high, it causes to increase the risk of condensation on the inner surface of insulation. For this reason, VDRF of an insulation material should be chosen within a range of value that would ensure minimum insulation thickness to prevent condensation. In the line of this study, taking into consideration the risk of condensation for both sides, it is recommended to select the VDRF in the range of 100-150.

- As the difference between indoor and outdoor relative humidity increases, the VDRF providing minimum insulation thickness required to prevent condensation decreases. Therefore, depending on the increase in the difference between indoor and outdoor relative humidity, it is recommended to prefer an insulation material with a lower VDRF.

- As the difference between indoor and outdoor temperatures increases, the VDRF providing minimum insulation thickness required to prevent condensation also increases. For this reason, depending on the increase in the difference between indoor and outdoor temperatures, it is recommended to prefer an insulation material with a higher VDRF.

- When VDRF of an applied insulation material, for a constant insulation thickness, is higher, it is recommended that thermal conductivity of insulation material should be lower.

- In insulation applications, when insulation materials with low VDRF are used, thermal conductivity of the insulation material does not have a significant effect on minimum insulation thickness that is required to prevent condensation.

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