AN INVESTIGATION OF TRANSIENT WATER VAPOR MIGRATION IN BUILDING EXTERNAL WALLS

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ABSTRACT

AN INVESTIGATION OF TRANSIENT WATER VAPOR MIGRATION IN BUILDING EXTERNAL WALLS

Building envelope design is very important for energy efficiency in the building due to control the mass and energy transfer between the internal and external environments. Additionally, this performance is also important for obtaining indoor air quality and comfort conditions in the built environment. The study aims to analyze the heat and moisture performance of the different building exterior wall types composed of the different structural elements and insulation materials. Two different analysis models were used for this study. The objective of the thesis is to predict the physical, chemical and biological problems in the building envelope that will arise due to condensation in the design stage. So, saving cost and time will be provided to consumers. In the scope of the thesis, the heat and moisture performance of 21 different wall sections that composed commonly used structural body elements (concrete, brick and aerated concrete) and insulation materials (XPS, EPS and MW) in different insulation situations (internal insulation, external insulation and non-insulated situation) were analyzed in steady and transient regimes. The interlayers with a risk of condensation were determined in the result of this study. The results of the two different analysis methods were evaluated and the differences of the methods were revealed. As a result of the study, it has been shown that the placement of the insulation material on the exterior side is more suitable for moisture.

ÖZET

BİNA DIŞ DUVARLARINDA ZAMANA BAĞLI SU BUHARI GÖÇÜNÜN İNCELENMESİ

Binalarda ise harcanan enerjinin çoğunluğunu ısıtma ve soğutma sistemleri kullanmaktadır. Bu nedenle, iç ve dış çevre arasında fiziksel bir bariyer olan yapı kabuğunun ısı ve nem performansı, binalarda enerji verimliliğinde oldukça büyük bir öneme sahiptir. Ayrıca yapılı çevredeki iç hava kalitesi ve konforunun sağlanmasında da bu performans önemlidir. Bu tez çalışmasında, farklı yapı elemanları ve yalıtım malzemesinden oluşan konut dış duvar tiplerinin ısı ve nem performansının analiz edilmesi amaçlanmaktadır. Çalışmada iki farklı yöntem kullanılmıştır. Kullanılan yöntemler arasındaki farklılıkların belirlenmesi de çalışmanın amaçlarındandır. Bu çalışma ile, yapıda yoğuşma nedeniyle meydana gelebilecek fiziksel, kimyasal ve biyolojik problemler; yapı tasarım aşamasındayken öngörülüp, kullanıcıya zaman ve maliyetten tasarruf etme imkânı sunulması hedeflenmektedir. Tez kapsamında, yaygın olarak kullanımı olan yapı (tuğla, beton ve gaz beton) ve yalıtım malzemeleri (XPS, EPS, MW) kullanılarak, farklı yalıtım konumları ile oluşturulan 21 farklı duvar kesiti; sabit ve değişken rejim şartlarında analiz edilmiştir. Sonuçlar nem denetimi açısından analiz edilmiş, riskli durumda olan duvar kesitleri belirlenmiştir. İki farklı analiz metodu sonuçları değerlendirilerek yöntemlerin farkları ortaya konmuş ve önerilerde bulunulmuştur. Çalışma sonucunda yalıtım malzemesinin, dış kısıma yerleştirilmesinin nem denetimi açısından daha uygun olduğu ortaya konulmuştur. Ülkemizde yayımlanmış TS 825 yönetmeliğinde belirtilen yöntemin sabit iklimsel veriler ve malzeme özellikleri kullanması, sadece buhar difüzyonunu hesaba katması nedeniyle nem denetimi açısından kısıtlı değerlendirme yapma imkânı vermektedir.

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CHAPTER 1

INTRODUCTION

1.1. Research Background and Problem Statement

With the increasing population in recent years, the need for energy and housing has increased, as well. Therefore, natural areas and resources began to be destroyed in an uncontrolled manner, then the ecological system broke down and the problem of global warming emerged. Researchers have tried to draw attention to this problem which affects the whole world and to produce solutions. After these searches, the sustainability term became a significant issue.

The issue of sustainability first raised in the United Nations Conference on Human Environment in Stockholm in 1972. This issue was developed by discussing at several international meetings such as the World Environment and Development Commission Report published in 1987, the Rio Conference in 1992 and the Johannesburg Summit in 2002 [1]. As a result of these conferences and meetings, terms such as energy conservation, energy-saving and energy efficiency have emerged.

In European countries, more than 40% of total energy, 30% of CO_2 emissions and 40% of synthetic waste are generated by the building sector [1].This situation shows how important the effects of the measures taken in buildings on energy conservation are. To reduce energy consumption in buildings, new technologies should be developed, sustainable building materials and construction techniques should be used, and structures should be built related to the natural environment.

A structure should be robust, durable, aesthetic, energy efficient, healthy and comfortable for users. The building envelope plays a major role in providing these facilities by creating a physical barrier between the inner and outer surroundings. The functions of the building envelope are explained with the following 4 main subheadings that are shown in Figure 1 [2].

1. **Controlling** the material and energy transfer between the inner and outer environment

2. **Supporting**, transferring or accommodating structural forces generated by the inner and outer environment or by itself
3. **Finishes** the space related to the inner and outer environment according to requests of occupants
4. **Distribution** of service systems for energy, ventilation, water and gas transport

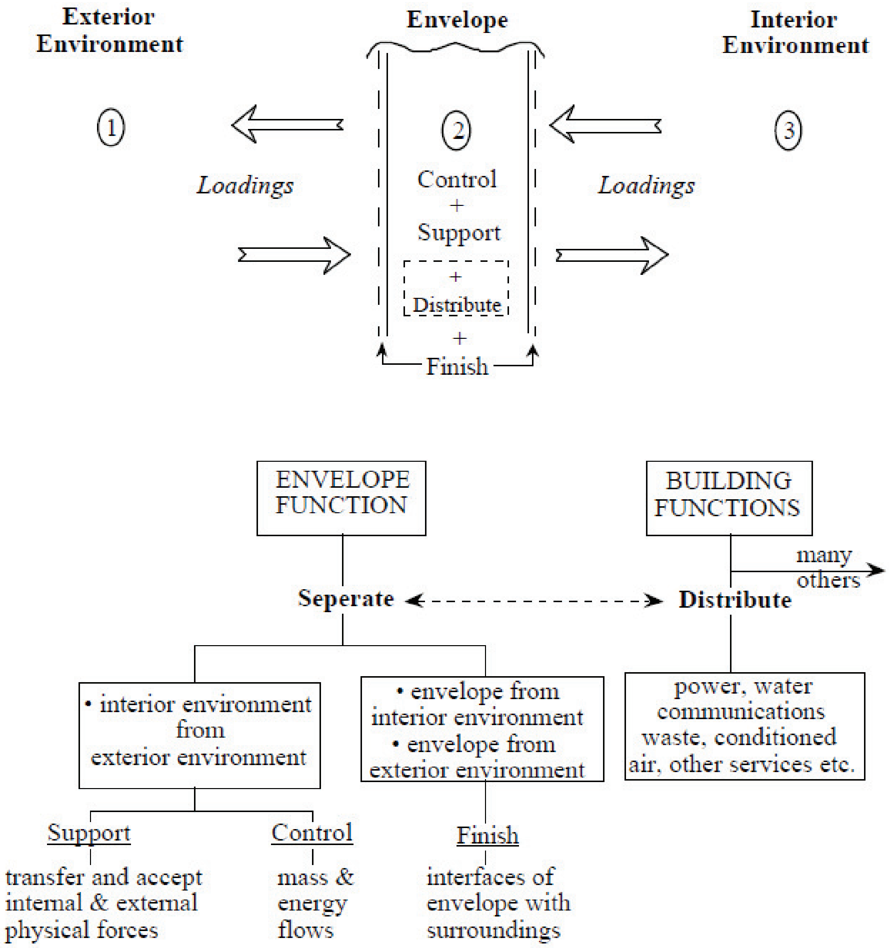


Figure 1. Functions of Building Envelope
(Source: Straube, J. F. Moisture In Buildings. *Ashrae J.* **2002**)

The building envelope involved the exterior wall, the roof and the flooring that related to the outer environment, have a function that prevents some of the environmental effects completely and some partially. Internal environment conditions should be kept at a certain level against external environmental factors that are constantly changing. Artificial systems are needed because it is not entirely possible to provide this situation only with the building envelope. Most of the energy used in buildings is due to the artificial systems used to resist the heating and cooling load.

At this time when energy conservation gains importance, controlling and managing the mass and energy transport between the inner and outer environment of the building envelope has gained considerable importance. The loads that the building envelope must control occur as a result of heat, air and moisture transfer.

New building materials and construction techniques have emerged with the development of technology. Thus, thin and multi-layered structural elements have replaced the thick outer walls of the building. The physical, chemical and structural properties of each material in the multi-layered structural element are different from each other. Each material has a different porous structure and it has the features of absorbing, storing, transport and desorption the moisture in its environment as far as its structure ratio. The moisture transfer is carried out by convection, diffusion, or both. Among the transfer types, vapor diffusion is the most effective and continuous in normal conditions. In the outer wall section, which consists of layers having different moisture permeability values, moisture does not pass rapidly from each layer and accumulates in some layers [3]. Because of some environmental impacts and problems in the construction phase, these accumulations which are called condensation occur. Condensation causes deterioration of the outer wall and problem about the performance of heat and moisture transfer within the building envelope. This situation enhances energy consuming in the building. Solving these problems is quite difficult in terms of physical and financial. For this reason, the problems that may occur should be foreseen; new solutions should be researched and developed.

1.2. Aim, Objectives and Scope of the Study

In accordance with TS 825 [4] regulations published in our country, insulation materials are used in order to increase the thermal performance of the building wall. These insulating materials increase the thermal resistance of the envelope and prevent energy loss, but in some cases affect the moisture performance of building envelope badly. The order of the elements within the structure is very important. Although the order of elements does not affect the thermal resistance of the structure, it affects the moisture transfer within the structure. The external wall has the most volume among the elements of the building envelope is building element. So, the exterior wall is selected for the analysis.

The study aims to analyze the heat and moisture performance of the different building exterior wall types composed of the different structural elements and insulation materials. Also, another aim of the study is revealing the differences in the used analyzing models.

Energy efficiency in buildings has been the target of many researchers as a current and interesting subject. One of the most important factors affecting energy efficiency is the heat and moisture transfer that occurs on the building envelope. Improving the heat and moisture performance of the building walls has become an important target not only for new buildings but also for extending the durability of the available and historical buildings. Designers can designate the heat and moisture performance of the building envelope at short notice under the favor of this study

The objective of the thesis to be predicted the physical, chemical and biological problems in the building envelope that will arise due to condensation in the design stage. Hereby, the thesis contributes to save time and cost for the users and to reduce the energy usage of the building.

The heat and moisture performance requirements expected from the building envelope, problems arising the moisture accumulation in the structure, moisture transfer and storage types in the building, the factors affected the moisture transfer within the structure were explained in the thesis.

In the scope of thesis, 21 different building exterior wall sections consisted commonly used structure body elements and insulation materials in different insulation situations were examined.

The used structure body elements of the wall are;

- Concrete
- Brick
- Aerated Concrete

The used insulation materials are;

- Expanded Polystyrene Foam - EPS
- Extrude Polystyrene Foam - XPS
- Mineral Wool – MW

The insulation situations in the wall are;

- Uninsulated situation
- Inner- insulated situation
- Outer-insulated situation

These building exterior walls were examined in;

- Steady-State Condition – specified analysis model in TS 825
- Transient Condition – numerical simulation tool by developed Künzel[5]

The differences of these analysis models were presented by evaluated calculation results in the scope of the thesis.

1.3. The Structure of the Thesis

The structure of this thesis is as follows. General information about heat and moisture transfer in building wall is detailed in Chapter 2. A review of the literature survey is provided in Chapter 3, the explanation of used analysis models, calculation procedures of these models and analysis results are described in Chapter 4. In Chapter 5, this thesis finalized with a comparison of two calculation models and a discussion of the presented study.

CHAPTER 2

HEAT AND MOISTURE TRANSFER IN BUILDING EXTERIOR WALL

2.1. Performance Requirements of External Walls

There is a responsibility to create a barrier between the external climatic conditions of the building exterior walls which are constantly changing and indoor conditions which must be kept constant in terms of user comfort. The extent to which this responsibility is achieved is evaluated as the performance of the outer wall. Wall properties such as temperature, heat, water and moisture, wind, etc. are the primary factors affecting these performances.

In most of the studies, the thermal performance of external walls is a priority issue. Problems caused by moisture accumulation directly affect thermal performance. If realistic results are to be obtained, it is necessary to consider thermal and moisture performance in relation to each other [3].

Thermal performance requirements;

- Less thermal losses in heating period
- Low thermal gains in cooling period
- Possibility of heat storage
- Keeping the inner surface temperature at the desired level
- Resistant to high and low temperatures
- Resistant to thermal deformation

Moisture related performance requirements;

- Prevention of changes and deteriorations in physical, chemical and biological performance of the wall caused by moisture accumulation
- Preventing bad outlook on the wall surface due to the accumulation of moisture

2.2. Moisture Problems in Building Walls

If moisture transfer in the wall structure cannot be achieved quickly, problems take place in the wall structure as a result of the accumulation between the layers. These problems increase the thermal conductivity of porous materials and cause structural damages. The problems that occur after the accumulation of moisture are listed below [6], [2], [7].

- Decreasing mechanical strength of materials
- Corrosion formation in metals
- Retarder effect
- Surface deterioration due to salts carried with moisture
- Visual defects on surfaces
- The increased moisture content in indoor air
- Mold and fungus formation
- Formation of cracks due to volume change in case of freezing, thawing
- Increased thermal conductivity of materials
- Degradation of concrete, stone and brick structure due to freeze-thaw

The condensed water on the floor causes the decay and swelling in wood, mold and fungus formation in the tile flooring. These problems are shown in Figure 2.

Figure 2. Damages on the building floor due to moisture accumulation

The condensed water on the wall causes the visual defects on surfaces, damage to paints and varnishes, dampness in the wall. These problems are shown in Figure 3.

Figure 3. Damages are on the building wall due to moisture accumulation

The condensed water on the roof causes the corrosion of metal building materials, mold and fungus formation in the roof, swelling, rotting and warping of wood building materials. These problems are shown in Figure 4.

Figure 4. Damages are on the building floor due to moisture accumulation

2.3. Resources of Moisture

Moisture reaches the building structure according to use case and the conditions that occur in the construction phase, before or after the construction at the construction phase. Causes of moisture in the building envelope; It is divided into 3 main parts as the resources from the external environment, the resources from the internal environment and the resources that occur during the construction phase [8], [2].

2.3.1. Resources from the External Environment

Causes of moisture arising from the external environment are environmental humidity, the amount of moisture in the air, rainwater, groundwater, etc.

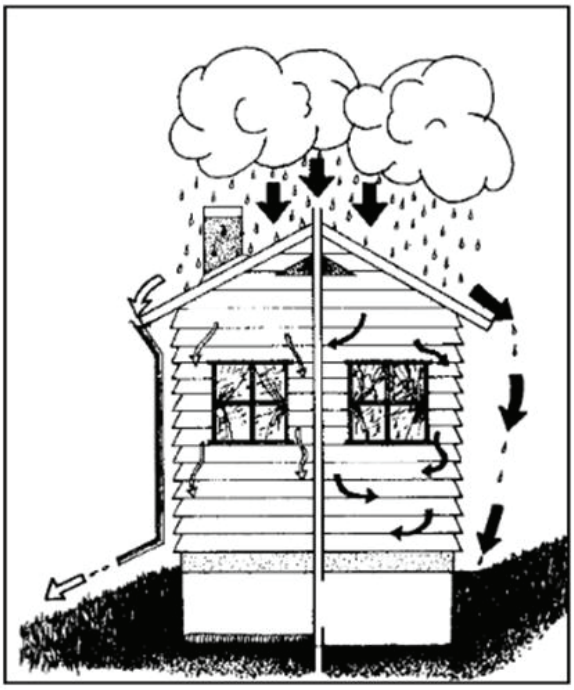


Figure 5. Moisture sources from the external environment
(Source: https://catalog.extension.oregonstate.edu/ec1437/html)

- Rainwater infiltrating into walls and floor
- Surface and groundwater infiltration into the structure as a result of the bad foundation drainage

- Infiltrating the moisture into the structure of the floorings and affecting the internal environment since floorings related to buried parts of the building undefended against moisture
- Penetrating water vapor into the building envelope in hot and humid weather
- Extraction of water vapor from the building envelope in cold weather

2.3.2. Resources from the Internal Environment

The causes of moisture originating from the indoor environment comprise of the indoor humidity, user activities, infiltrations, and actions in the indoor and similar sources.

- Moisture caused by the respiration of humans and animals in the restricted area
- Vapor in the kitchen section, vapor from cooking, vapor coming out of the bathroom and shower, and moisture generated during the drying of wet laundry
- The effect of the systems used for heating on the indoor moisture content
- The effect of vapor and heat exiting some tools used in the structure on the moisture content of the air

2.3.3. Resources from Structure of the Building

The causes of moisture arising from the structure consist of moisture accumulation in building materials as a result of the rain effect during the construction phase, problems in installation systems in the wall element, cracks in the roof and wall elements and water absorption feature due to the porous structure of the building materials.

- As a result of rain and environmental factors that occur during the construction phase, moisture accumulation in the building materials bundle
- Condensation caused by poor insulation in plumbing pipes
- Infiltration into the interior due to cracks in the building envelope
- Moisture accumulation in between some layers due to different transfer speed arising the different pore structure of the materials

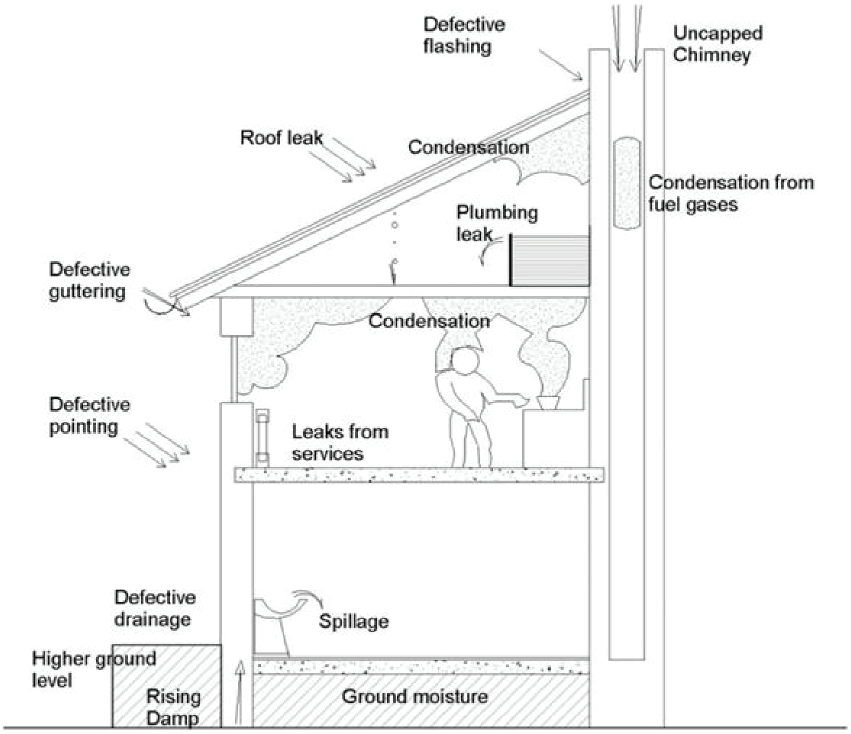


Figure 6. Moisture sources from indoor and structure of the building (Source: Preventing Dampness Related Health Risks at the Design Stage of Buildings in Mediterranean Climates: A Cyprus Case Study)

2.4. Types of Moisture Transportation and Storage

Moisture enters the building envelope for different reasons, is transported with different effects and stored for a certain period. The moisture transport in the building envelope takes place in 4 different ways [2], [7]. These;

- Liquid Gravity Flow (1)
- Capillary Action (2)
- Air Movement (3)
- Vapor Diffusion (4)

Liquid gravity flow; is one of the most important moisture transport types. A large amount of liquid is transported in the cracks, openings, pipes or air cavities created by gravity. Flow by gravity occurs in larger pores than flow by capillary suction. Liquid water can infiltrate into the building with the effect of gravitational force from the cracks in the building envelope and foundation structure. So, big problems occur in the building. This type is shown as number 1 in Figure 7.

Figure 7. Types of moisture transfer types to the building. (Source:http://blog.drummondhouseplans.com/2011/07/13/keeping-water-out-of-buildings/)

Capillary action; is the movement of liquid through a porous material from the high concentration region to the low concentration region. The more powerful capillary adsorption occurs in the smaller pores. It occurs slowly but has a long-lasting effect. It is more effective in soil and rain related parts of the structure. This type is shown as number 2 in Figure 7.

Air movement; enables water vapor to move between channels and distribute in the cavity. It causes condensation due to openings in the envelope. It is the main reason for interstitial condensation due to move into openings in the envelope. It causes to moisture leak into the building after the rain. Very small air flows are more effective than vapor diffusion. This type is shown as number 3 in Figure 7.

Vapor diffusion; occurs as a result of the movement of the water vapor from the environment where the partial water vapor pressure is high to the lower environment. Diffusion allows the movement of vapor, in the air or in the air inside porous materials. Water vapor diffusion is also involved in the transport of water vapor into the building where it can sometimes condense. Under normal conditions, vapor diffusion is the type of moisture transport that is constantly occurring and the most effective among the moisture transport types. This type is shown as number 4 in Figure 7.

Moisture is stored in the structure of the building elements created an exterior wall due to sorption and capillary action or accumulate as normal water.

2.5. Factors Affecting the Heat and Moisture Transfer

Depending on the season, climatic conditions and the wall properties affected by this change greatly affect the heat and moisture transfer in the building envelope. Factors affecting the heat and moisture transfer in the building envelope are external climatic elements, internal climatic elements and properties of the material.

2.5.1. Resources from the External Environment

Solar radiation, outside air temperature, outside air humidity and wind (air movements) are climate components in the outside environment. These elements are measured in weather stations located in the regions by Turkish Republic General Directorate of State Meteorology Affairs. These measurements provide hourly, daily, monthly and annual data on the mean, minimum and maximum values [9].

- Outside Air Temperature

Temperature values are affected by properties of the surface, sun motion, sky condition, the interaction between the earth and atmosphere, the intensity of solar radiation. In the present study, outdoor air temperature values incorporate in the analysis as hourly data. The outside air temperature is important factor for hygrothermal behavior of building envelope because of that the moisture content changes with temperature.

- Outside Air Humidity

Atmospheric air is a mixture of dry air and water vapor. The amount of water vapor in the air is called moisture and the air containing water vapor is called moist air. It can carry water vapor in the air and this rate varies with temperature. Some terms for moisture are described in the following section.

Absolute humidity; is the unit mass of the water vapor in the unit volume of moist air. The unit is gr / m3 or kg / m3.

Specific humidity; is the unit mass is the mass of water vapor in moist air. The unit is gr/kg.

Relative humidity; is the ratio of the amount of water vapor contained by the air in certain conditions or the partial pressure it generates to the amount of water vapor contained by the saturated air in the same conditions or the saturated vapor pressure. Air humidity is explained by this term. The relative humidity value is repeated in 24-hour periods and is defined by the sinus curve.

- Solar Radiation

Radiation is the energy that is emitted from particles in the form of electromagnetic waves (or photons) as a result of the changes in the electronic patterns of atoms and molecules[10].

As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected. This is called diffuse solar radiation. The solar radiation that reaches the Earth's surface without being diffused is called direct beam solar radiation. The sum of the diffuse and direct solar radiation is called global solar radiation.

As regards solar radiation from building envelope; absorptivity, reflectivity and transparency are the optic factors that determine saving in solar energy. Heat conduction coefficient, heat storage capacity, heat radiation capacity, time lag and damping ratio are the thermophysical qualities that determine the amount of saving in solar energy [9].

- Wind

Wind is air in motion relative to the earth's surface. It moves from high pressure to low pressure. As the wind approaches the earth, its velocity and direction change over time. Heat convection and vapor diffusion are affected by wind direction and velocity. For this reason, hygrothermal behavior of building envelope relates to wind. Predominant wind direction, wind velocity, number of blowing, etc. are important key parts of designing of structure for energy saving and occupant’s comfort [11].

- Rainfall

Rain is one of the predominant sources of moisture in the building envelope. The water accumulated on the wall surface under the effect of rain reaches the internal structure through cracks and voids in the wall structure. Water in the wall structure leads to the decomposition of the material as a result of crystallization of the salt it contains. Hence, control of rain penetration and absorption is a fundamental function of the building enclosure, and a major part of its moisture control functions.

2.5.2. Internal Climatic Elements

The internal climate factors affecting hygrothermal behavior of building envelope are the indoor air temperature and indoor relative humidity values.

The internal air temperature changes depending on performance of exterior wall, internal heat resources, change of external temperature, and performance of heating-cooling mechanism, etc. Internal air temperature can be adjusted to the optimum level according to different functions and user requirements.

The internal air humidity changes depending on temperature, related factors with temperature, internal moisture resources, water vapor permeability value of wall. Internal air humidity can be adjusted to the optimum level according to different functions and user requirements.

2.5.3. Properties of Material

Properties of material affect the heat and moisture transfer in the building envelope. These properties are affected the humidity. Humidity of the building material is related with water and water vapor properties of this building element.

In this part, some properties of building material in exterior wall which are affecting the moisture transfer and be affected from moisture transfer are explained.

- Water vapor diffusion resistance factor, μ-value (dimensionless)

The μ-value represents the ratio of the diffusion coefficients of water vapor in air and in the building material and has therefore a simple interpretation: it is the factor by which the vapor diffusion in the material is impeded, as compared to diffusion in stagnant air. For very permeable materials, such as mineral wool, the μ-value is thus close to 1, whereas it increases for materials with greater diffusion resistance [12].

- Vapor diffusion thickness, S_d-value

For a material layer with diffusion resistance factor μ and thickness s, the product $\mu * s$ thus gives the thickness which a stagnant air layer would need in order to have the same diffusion resistance. This "S_d-value" or "vapor diffusion thickness" expresses the diffusion resistance of a layer in a form which is easily understood and applied [13].

Since the definition of the S_d-value contains the thickness Δx of the layer, the S_d-value is a property of the given layer, not of the material itself. Two layers made from the same material but with different thicknesses will have different S_d-values, but in both cases the material will have the same μ-value. This;

$$S_d = \mu * d \tag{1}$$

Where;

S_d: Vapor diffusion thickness (m)

μ: Diffusion resistance factor (-)

d: The material layer thickness (m)

- Capillary water absorption coefficient

Water absorption due to capillary action is a phenomenon that occurs through the difference between the fluid’s surface capillary pressure and its gravity pressure, which forces fluid movement until balance is established. Capillary pressure increases with decreasing capillary diameter. Water absorption coefficient is difficult to measure because of depending on temperature and material structure, so it is regarded as a coefficient. It changes depending on temperature and material humidity [11].

- Moisture Storage Function

In usual condition, moisture is accumulated in pores of material because of sorption. Water and moisture stored in material pores by either capillary action or sorption increase the vapor diffusion activity in the wall [13].

- Thermal Conductivity Coefficient

Thermal conductivity λ is defined as ability of material to transmit heat and it is measured in watts per square meter of surface area for a temperature gradient of 1 K per unit thickness of 1 m. Unit of thermal conductivity coefficient is W/mK. The main factors affected the thermal conductivity are the density of material, moisture of material and ambient temperature. With increasing density, moisture and temperature, the thermal conductivity also increases to [14].

- Specific Heat

A specific amount of energy is required by the same mass of every substance to change its temperature by 1°C. The specific heat of building material changes depending on temperature. Units of specific heat are Wh/kg°C or J/kg°C. It affects vapor diffusion by affecting temperature distribution in the wall.

In addition to these material properties which affect the heat and moisture transfer in the exterior wall, the orientation of the wall, the thickness and the order of the layers forming the wall also have a significant effect on the hygrothermal behavior of the wall.

2.6. Analyzing Methods for Heat and Moisture Transfer in Building Envelope

Moisture transfer in building is complex process because of depending on several physical factors [14]. Some knowledge is required to analyze the hygrothermal performance;

- Geometry of the enclosure
- Interior and exterior environment boundary conditions
- Material properties and their variation with temperature, moisture, etc.
- Physics, chemistry, thermodynamics, and mathematics of combined heat, air, and moisture transport
- Performance thresholds

Several method and models are developed for analyzing the hygrothermal behavior of building [14]. These methods and models are separated based on various parameters;

- Dimension (one, two, or three dimensional),
- Time (steady-state, quasi-static, or dynamic),
- Quality and availability of information,
- Stochastic nature of each data set (e.g., material properties, weather, construction quality).

Environmental factors change with time and affect the properties of building material related to hygrothermal behavior of wall correspondingly. Therefore, time is major key factor in the research area and theoretical methods can be divided into steady state methods and transient methods. In steady state methods, environmental climate elements such as temperature, relative humidity, solar radiation are regarded as constant for continuous or certain time. On the contrary, time-dependent changes of external climate elements are took into consideration in transient methods.

2.6.1. Steady- State Regime Analyzing Method

The most used methods are dew point method, the Glaser diagram, and the Kieper diagram. These methods hold a candle to saturation pressures and vapor pressures within the envelope. Saturation pressures are calculated based on temperatures within the envelope. Vapor pressures are calculated by simple vapor diffusion equations. If the calculated vapor pressure is above the saturation pressure at any point within the envelope, condensation is indicated. Glaser diagram is commonly used in Europe; the dew point method is used in North America. The main difference of methods is based on the graphical procedures [14].

2.6.1.1. Dew-Point Methods

The dew point method is based on the following diffusion equation and definitions,

$$w = -\mu * \Delta p / d \tag{2}$$

Where;

w: Vapor flow per unit of area, kg/m^2 s

μ: Water vapor permeability, kg/m·s·Pa

p: Vapor pressure, Pa

d: Flow path or thickness of the material, m

Water vapor resistance, Z, is the inverse of the permeance and is expressed in m/s

$$Z = d/\mu \tag{3}$$

2.6.1.2. Glaser Diagram

The Glaser diagram is a variation on the dew point method. The Glaser diagram is based on the following diffusion equation and definitions,

$$w = -(\delta'/\mu') * \Delta p/d \tag{4}$$

Where;

δ': Diffusion coefficient of water vapor in air, s

μ': Diffusion resistance factor of the material

d: Flow path or thickness of the material, m

The term water vapor diffusion coefficient is often used instead, defined by

$$\delta = \delta'/\mu' \tag{5}$$

Vapor diffusion resistance is again defined as

$$Z = d/\delta \tag{6}$$

The only difference between the Glaser diagram and the conventional dew point method lies in the horizontal axis of the diagram. Rather than using thickness of the materials, the Glaser diagram uses the vapor diffusion resistance as the horizontal axis [14].

2.6.1.3. Kieper Diagram

The Kieper diagram was first introduced by Kieper and described in greater detail by TenWolde. As with the dew point method and the Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory. The advantages of this method are:

- The same diagram can be used for different wall configurations, as long as indoor and outdoor conditions are not changed, and
- The calculation does not need to be repeated if condensation is indicated.

2.6.2. Transient Regime Analyzing Method

There are methods which analyzing the heat and moisture transfer by taking into consideration other moisture transport types and heat transport effects besides only vapor diffusion in the literature.

Husseini method and Husseini-Ricken method are the main methods analyzing the vapor diffusion effect. In addition to them, Kiessl, Kerestecioglu, Kupke and Pfrommer developed methods which analyzing other moisture transfer types and temperature effects [3].

2.6.2.1. Husseini Method

One dimensional vapor diffusion and effect in homogeneous, single layer wall is calculated with this method by using variable internal and external climate data. Vapor diffusion is taken as a basis as moisture transfer type due to vapor pressure difference. Heat and moisture transfer are considered separately. Moisture performance, moisture distribution and thermal performance of the element can be evaluated according to the temperature distribution at the end of the desired period.

2.6.2.2. Husseini - Ricken Method

This method is developed by using Husseini Method for evaluating performance of multi-layer elements. It cannot be used in the situation that structural elements are directly related to water or that temperatures exceeding temperatures, which are considered normal temperatures in building physics.

2.6.2.3. Kiessl Method

Kiessl examined vapor diffusion as two parts, temperature and moisture-related portion separately. He defined a new material-independent moisture potential which is continuous in multi-layered structural elements for the capillary transport. This model contributes to the calculation of capillary moisture transport across material boundaries and the equilibrium states in the hygroscopic region without complementary functions [15].

2.6.3. Advanced Computers Models

There are several computer models to analyze the hygrothermal behavior in the building. Some of them are for 1-D analysis, some of 2-D analysis.

These models differ from each other in terms of driving potential approach and dimensional. The most commonly used models of advanced computer models are TRATMO, MATCH, MOIST, DELPHIN, WUFI and LATENITE

TRATMO; is the transient analysis code for thermal and moisture physical behaviors of constructions. Kohonen developed the model which used vapor pressure and temperature as driving potentials [16].

MATCH; is a one-dimensional model that accounts moisture transport by diffusion and liquid suction. In the hygroscopic regime, the sorption isotherm is used, and moisture transport is assumed to be by vapor flow only, driven by vapor pressure differences and defined by the vapor permeability of the material [14].

MOIST; is developed by Burch for researching the 1D heat and moisture in the building envelope. For moisture modeling, vapor pressure gradients are used as vapor flow-driven and capillary pressure gradients as capillary transport driven. The individual construction layers can be defined in the program by users in analyzing the temperature and moisture content as a function of time of year [17].

DELPHIN; is a 2D heat, air, moisture and salt in porous material analysis model. The construction materials and constructions behavior are predicted close to reality by incorporating real climatic boundary conditions. It is used to develop the building materials for optimal hygrothermal performance, durable buildings and energy consumption [18].

WUFI; is developed by Hartwig M. Künzel for transient 1D, 2D heat and moisture transfer in building and whole building. This model uses a full moisture retention function, from the sorption isotherm and suction curve. It uses standard material properties and measured climatic boundary conditions. Estimating drying time of initial moisture, the rain effect on the building envelope, the risk of interstitial condensation can be predicting with this model [5].

LATENITE; is developed by Karagiozis and Salonvaara for 2D heat and moisture transfer. One, two, or three dimensions can be modeled, but only one- and two-dimensional calculation results have been presented. Airflow, wind, moisture sources and driving rain deposition can be included in the analysis. It is used not only for solving building envelope, but also for simulating the interaction between the building envelope and the indoor air [19].

CHAPTER 3

LITERATURE REVIEW

Nowadays, the consumption and conservation of energy in buildings are very attractive research topics among researchers. In this part, some studies are explained chronologically by summarizing.

The first research which was Condensation in Walls and Attics was written by Teesdale made in the 1930s. This publication was about calculation of diffusion resistance. At the end of the 1950s, H. Glaser developed a calculation method for vapor diffusion in the wall and condensation within the wall. The calculation model bearing the name of Glaser is still one of the most used methods in Europa. Researches started to work the coupled of heat and moisture transport topics in the 1960s. O. Krischer, J. S. Cammerer, Künzel, A. De Vries, B. H. Vos, L. E. Nevander and A. Tveit were the commonly known researchers contributing to analyze the heat and moisture transport [20].

Künzel [5] developed a new method for calculating time-dependent and two-dimensional heat and moisture transfer in building components using basic parameters in building components. He first investigated the moisture storage and transfer mechanisms and the effect of these mechanisms on heat transfer. In the calculation stage, in addition to exterior temperature and relative humidity, solar radiation and rain load were also considered. WUFI computer program model developed in this study is among the most widely used and reliable programs today [5].

Altun [3] enhanced the new approach to investigate the effect of vapor diffusion on the heat and moisture performance of the wall. When developing the calculation model, using real interior and exterior climate data, changes in the physical properties of external wall materials as a result of time-related and various environmental factors and the effects of these changes on vapor diffusion and thermal performance were taken into consideration. In the scope of the study of Altun, the provinces were determined from five different climate zones in Turkey. Exterior climate data were constituted by averaging ten-year climate data of these provinces. Interior climate data was accepted as constant. Insulation material was placed in different positions and these different wall types were examined. The results are presented graphically [3].

Heperkan [21] et al. developed a computer program that identifies the point of condensation within the building material, facilitating vapor diffusion and condensation calculations. In this study, heat and moisture analysis were performed in a building structure consisting of 8 different materials. As a result of the study, it was revealed that the construction materials should be sorted according to the diffusion technique in order to avoid condensation [21].

Karagiozis and Salonvaara [19], new model and approach were developed to analyze holistic moisture engineering. In this study, new model was utilized to specify the drying performance of aerated concrete blocks using LATENITE 3.0 VTT program. Structure elements that constitute the building envelope such as wall and roof were incorporated into the analysis. Real weather data was using for the boundary conditions in the calculation. The initial construction moisture was evaluated as the source of the water. A rectangular building was modeled by explaining the behavior of water vapor during entry and exit of the building. This modeled building was analyzed for two situations that one with 25 mm expanded polystyrene installed on the exterior of the building and the other without the insulation. Also, the effect of external insulation on drying performance was investigated with this analysis [19].

Yücel [22] carried out heat and moisture transfer analysis by creating cross-sections covered with different building materials. With this analysis, it was aimed to provide the practitioners with the opportunity to select the appropriate cross-section. The study was conducted under the fixed regime conditions and the method presented in TS 825 regulation. In this study, climatic data of Edirne province which is in second degree day region among four-degree day zone determined by TS 825 regulation was used. As a result of the study, it was indicated that it was wrong to stop the vapor movement and it was appropriate to form the wall cross-section with the most appropriate layer sequence [22].

Sever [23] analyzed the heat and moisture transfer in light steel framework wall structures were examined. Within the scope of the study, four provinces were selected to represent the four-degree day zone in the TS 825 regulation. Heat and moisture transfer calculations of the sections, which were formed by covering the light steel framework systems with widely used and newly developed building materials, were made by using the climate data of the selected provinces and graphs were created. The study was carried out according to winter comfort under constant regime conditions. It was indicated that the materials with high thermal insulation properties should be applied to the outer part or near the outer part of the construction in order to avoid condensation [23].

Umaroğulları [11] performed the experimental and numerical heat and moisture transfer analysis of eight different reinforced concrete building envelope sections. The study was performed by using real climatic data of provinces in five different climatic zones. Section analysis was performed using WUFI 2D-3 computer program and the results were compared with the experimental results. The aim of this study is to present the most suitable order among concrete vertical envelope elements to the user, to prevent problems caused by condensation and to extend the durability of the building [11].

In the paper published by Pehlevan, Yaşar and Maçka [24], WUFI and MOIST computer models were introduced, and the hydrothermal behavior of the sample wall construction was analyzed with these two computer models and the results are compared. As a result of the study, the suitability of used the computer models was discussed and it was determined that the two programs were suitable. WUFI program model was indicated to be easier to use and more materials available in the database. It was stated that utilization of MOIST is difficult for the users on the grounds that lots of input data and weekly calculation instead of daily calculation [24].

In the thesis of Selnta Chasan [25], temperature, water content, moisture content and condensation conditions of the external wall elements were examined with WUFI 2D-3 computer simulation program by using the climate data of Edirne province. In this study, the most used structure wall systems in Turkey that consists of brick, aerated concrete, bims block were analyzed by covering with external insulation material. Each core material was examined with 3 different (EPS, XPS and MW) insulation materials by using climate data of Edirne province. Also, the effects of core and insulation material changes on temperature, humidity and water content were investigated [25].

Edis and Kuş [26] introduced software program which is analyzed hygrothermal behavior of building envelope in this study. A type wall was analyzed with WUFI 2D and usage of software program was exemplified with this analysis. It was explained which situations can be analyzed during the establishment of the numerical model, the calculation part and the evaluation of the results. At the end of the study, it was remarked that the processes of selecting the software program which evaluated hygrothermal behavior performance of the wall and planning the simulation are important to get an effective result [26].

Chang and Kim [27] investigated the effect of moisture transfer on total building performance based on heat and humidity simulation. In this study, the hygrothermal performances of wood and concrete building elements in Korea were analyzed using WUFI Pro 5.3 simulation model. Moisture content, condensation risk and mold formation risk were determined with this study [27].

Mıhlayanlar [28] analyzed the masonry wall section of the traditional building in terms of heat and moisture transfer with the backing of WUFI2D-3 simulation program in this study. Annual temperature, water and moisture values of the wall section were calculated with the analysis. Simulation was performed by using climate data of Edirne province under periodic regime conditions. As a result of the study, it is determined that the stone wall section did not pose a risk from the condensation and that the section would not have any problems in terms of hygrothermal performance [28].

You et al. [29] examined condensation on the inner surface of buildings in high humid climates and typical zones in which condensation occurs experimentally and numerically in the study. Simulation results obtained with FLUENT software were compared with experimental data. The effect of exterior temperature, humidity and wind speed on condensation were investigated. Two inferences were made to prevent the formation of moisture as a result of the study. Firstly, it was indicated that if the outside air temperature increases, the condensation start time shortened, thus reducing the amount of water and moisture accumulation. Secondly, it determined that the condensation time increase as a result of the increase in the humidity level in the outdoor environment and therefore the effect of the condensed moisture amount increase. The regions where condensation occurred most frequently in the building envelope were specified as the corner of the walls, the joints of the vertical walls and the joints of the vertical wall with the ceiling [29].

Cascione et al [30]. compared the Glaser method which is one of the steady regime calculation methods and WUFI Pro computer simulation program which is one of the transient regime calculation methods in the study. In the evaluation, not only the condensation between the layers superficially, but also biological approaches, freezing and thawing cycles and corrosion were considered. Nine different outer wall sections were formed by using three different insulation materials and three core materials. The wall sections were analyzed by two methods using climatic data of Milan and Bari. The results obtained were compared and then summarized with the aid of a table. In this table, it was indicated whether the wall sections are suitable for condensation under the created conditions. When the insulation material was applied to the outside, it is stated that it did not create condensation risk by giving similar results in two methods. As a result of the application of insulation material to the inner part of Glaser method, it is stated that it gives more coherent results than dynamic simulation model. It was clarified that the results of the simulation programs are directly related to the input data and if the more real data is entered, the more real results can be obtained [30].

Kaynaklı [31] aimed to optimize the insulation thickness of the outer wall structures formed by using the same thermal resistance insulation materials by analyzing the condensation situation in the study. Insulation thickness and 3 different insulation application types (internal, external and sandwich) were analyzed. In addition, with the analysis made for different temperature and relative humidity values, it was determined which climatic conditions gave better results for implementations [31].

In the study of Bademlioğlu and Canbolat [32], using climate data of Bitlis, minimum insulation thickness was calculated according to months considering the risk of condensation on the externally insulated wall section. The effect of interior temperature on the insulation thickness was investigated by using different indoor temperatures. At the end of the highest risk of condensation was determined in February and the required insulation thickness was determined as 0.104 m [32].

In the studies carried out in our country, WUFI simulation model and the calculation method specified in TS 825 Directive on the Thermal Insulation in Buildings [4] were utilized separately to analyze the heat and moisture transfer in the building wall. This study differs from other studies due to evaluate the results obtained with these two commonly used methods and determining the advantages/disadvantages of those methods. At the end of this thesis, it is drawn the conclusion that the calculation model specified in TS 825 is incomplete and inadequate in consequence of the changing climate conditions and accepted assumptions.

The study done by Cascione et al. is one of the studies like this thesis. This thesis differs from the study of Cascione et al. in terms of the used climate data and material properties which are type, size, chemical and biological properties of used materials. Similar results were obtained despite the use of different materials and climate data. The μ-value of materials and the location of insulation materials have significant roles in the hygrothermal performance of the building walls.

CHAPTER 4

ANALYZING HEAT AND MOISTURE TRANSFER IN BUILDING EXTERIOR WALL

Material properties affect the hygrothermal behavior of the building envelope and are determinative as the performance of the envelope. Material selection and array within the structural element is a very important key point for the heat and moisture transport in the structural element of the building. In present study, time-dependent and time-independent hygrothermal behaviors with respect to different positioning of structural materials in the wall structure were analyzed via a diagram model for time-independent regime and a software model for time-dependent regime. Also, in this study, 21 different sections were constituted respect to with 3 different envelope body elements, 3 different insulation materials and 3 different positions of insulation material in the structure.

4.1. Building Envelope Sections Analyzed in Models

These sections were created with 3 different structure body elements, 3 different insulation materials, and 3 different insulation situations in the wall structure. These materials and situations are respectively;

The used structure body elements of the wall are;

- Concrete
- Brick
- Aerated Concrete

The used insulation materials are;

- EPS (Expanded Polystyrene Foam)
- XPS (Extrude Polystyrene Foam)
- MW (Mineral Wool)

The insulation situations in the wall are;

- Uninsulated situation
- Inner- insulated situation
- Outer-insulated situation

The thickness of envelope body element was specified as 20 cm for each material type. XPS (extrude polystyrene foam), EPS (expanded polystyrene foam) and MW (mineral wool) were profited as insulation material. Thickness of insulation material was determined by taking into consideration U_w value specified in TS-825 Directive on the Thermal Insulation in Buildings and was different value for each used envelope body element. The specified U_w values are specified in appendix A. Calculated insulation thicknesses are shown in Table 1.

Table 1. Type and Thickness of Materials

Structure Type	Material	Thickness (m)
Plastering	Cement Plastering	0.03
	Lime Plastering	0.02
Body Element	Concrete	0.2
	Brick	0.2
	Aerated Concrete	0.2
Insulation for Concrete	Mineral Wool	0.09
	Extrude Polystyrene Foam	0.07
	Expanded Polystyrene Foam	0.09
Insulation for Brick	Mineral Wool	0.08
	Extrude Polystyrene Foam	0.06
	Expanded Polystyrene Foam	0.08
Insulation for Aerated Concrete	Mineral Wool	0.03
	Extrude Polystyrene Foam	0.03
	Expanded Polystyrene Foam	0.03

Uninsulated wall type section is given in Figure 8. The uninsulated exterior wall situation, which is respectively 3 cm cement plastering on outside, 20 cm structure body element (brick, concrete, aerated concrete) and 2 cm lime plastering on inside. Aerated Concrete is selected to be shown in the sample Figure 8.

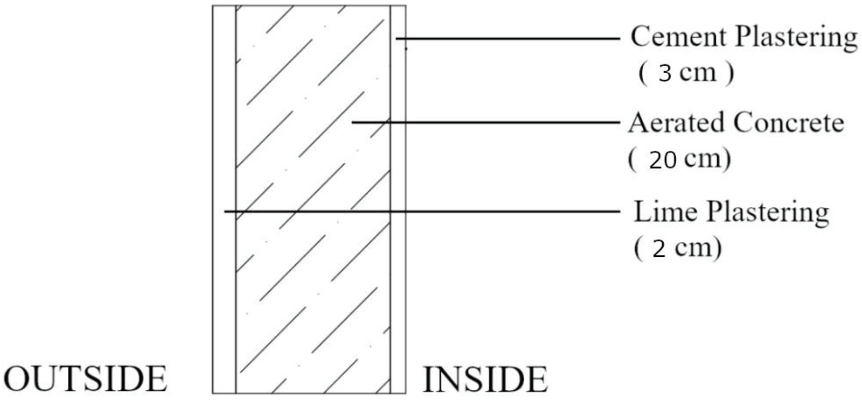


Figure 8. Sample Building Wall Section for Without Insulation Type

The external insulated wall type section is given in Figure 9. The external insulated situation in order of 3 cm cement plastering on outside, variable size XPS, EPS and MW according to envelop body element type, 20 cm envelope body element (concrete, solid brick and aerated concrete), and 2 cm lime plastering on inside. This section type is created by using separately all insulation material type for each envelope body element. Concrete is selected to be shown in the sample Figure 9.

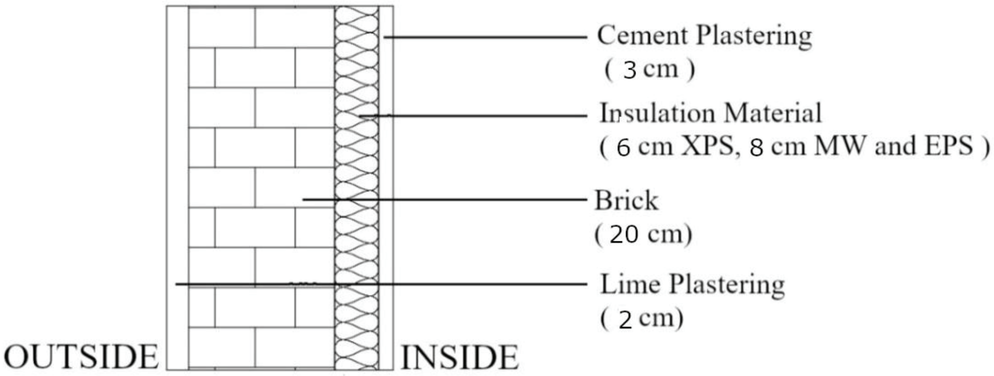


Figure 9. Sample Building Wall Section for External Insulation Type

The internal insulated wall type section is given in Figure 10. The internal insulated situation in order of 3 cm cement plastering on outside, 20 cm envelope body element (concrete, solid brick and aerated concrete), variable size XPS, EPS and MW according to envelop body element type, and 2 cm lime plastering on inside. This section type is created by using separately all insulation material type for each envelope body element. Brick is selected to be shown in the sample Figure 10.

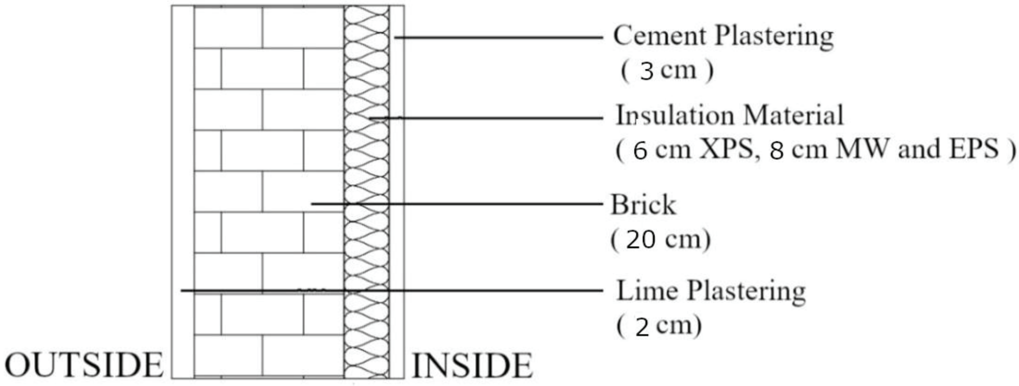


Figure 10. Sample Building Wall Section for Internal Insulation Type

4.2. Operation Scheme

The study was carried out as indicated in the following operation scheme:

1. Calculation required insulation thickness for each wall types according to U_w values specified in TS 825 [4].
2. The control condensation test was done for each exterior wall type by using temperature and relative humidity values of Erzurum provinces specified in TS 825.
3. Selecting the climate data to be used in the study from the WUFI database by bearing in mind that used climate data in the previous phase.
4. The condensation test specified in TS 825 was remade by using the selected climate data from the WUFI database.
5. The condensation test was done by using numerical simulation tool-WUFI by using the selected climate data from the WUFI database.
6. Evaluating the results of two different analysis models and determining the differences between them.

4.3. Climate Data

Turkey has been classified into 4 level-day zones as per TS-825 standard[4] according to their needs for energy. These zones are given in Appendix B. 1st zone stands for the zone that needs the least amount of energy; 4th zone stands for the zone that needs the highest amount of energy. İzmir, İstanbul, Ankara and Erzurum were selected for 1st, 2nd, 3rd, and 4th zone, respectively. The climate data of these provinces are shown in Table 2 and 3. The climate data of them was used for 1st calculation. As a result of this calculation, it was determined climate data be selected from the WUFI[12] database should be closer to which climate data. Condensation risk occurs mostly with Erzurum climate data, therefore Holzkirchen was selected for the analysis. The climate data of Holzkirchen is like Erzurum data, but it is colder and more humid than Erzurum. The climate data of Erzurum and Holzkirchen are shown in Table 3. This situation is useful to analysis the hygrothermal behavior of the wall in the worse weather.

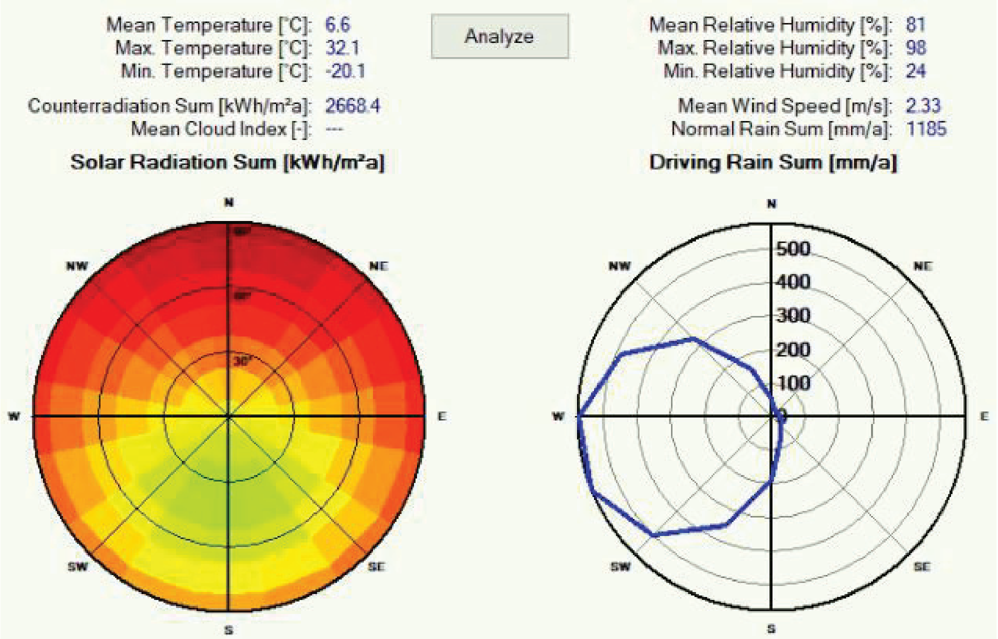
Table 2. Temperature and Relative Humidity Values of İzmir, Istanbul and Ankara

	İzmir		İstanbul		Ankara	
	Temperature (^{O}C)	Relative Humidity (%)	Temperature (^{O}C)	Relative Humidity (%)	Temperature (^{O}C)	Relative Humidity (%)
January	8.4	71	2.9	79	-0.3	76
February	9	69	4.4	76	0.1	71
March	11.6	67	7.3	75	4.1	65
April	15.8	64	12.8	74	10.1	62
May	21.2	60	18	74	14.4	59
June	26.3	53	22.5	70	18.5	55
July	28.7	51	24.9	71	21.7	49
August	27.6	54	24.3	74	21.2	48
September	23.5	58	19.9	75	17.2	52
October	18.5	64	14.1	80	11.6	62
November	13	70	8.5	79	5.6	72
December	9.3	73	3.8	80	1.3	78

Holzkirchen is a market town in Bavaria, Germany. The climate analysis of this city is shown in Figure 11. The average temperature in Holzkirchen is 6.6 °C. The maximum temperature is 32.1°C. The minimum temperature is -20.1°C. The average relative humidity is 81%. The maximum relative humidity is 98% and the minimum relative humidity is 24%. The average wind speed is 2.33 m/s. The normal rain sum is 1185 mm/a. The rain mostly affects the west direction.

Table 3. Temperature and Relative Humidity Values of Erzurum and Holzkirchen

	Erzurum		Holzkirchen	
	Temperature (^{O}C)	Relative Humidity (%)	Temperature (^{O}C)	Relative Humidity (%)
January	-5.4	78	-6.2	88
February	-4.7	77	-3.1	84
March	0.3	75	-0.1	80
April	7.9	67	7.3	78
May	12.8	63	10.1	72
June	17.3	59	16.1	71
July	21.4	54	16.8	77
August	21.1	51	14.5	83
September	16.5	54	13.8	81
October	10.3	66	2.6	84
November	3.1	75	1.6	88
December	-2.8	79	-2.6	89


Mean Temperature [°C]: 6.6
Max. Temperature [°C]: 32.1
Min. Temperature [°C]: -20.1
Counterradiation Sum [kWh/m²a]: 2668.4
Mean Cloud Index [-]: ---
Mean Relative Humidity [%]: 81
Max. Relative Humidity [%]: 98
Min. Relative Humidity [%]: 24
Mean Wind Speed [m/s]: 2.33
Normal Rain Sum [mm/a]: 1185

Solar Radiation Sum [kWh/m²a]

Driving Rain Sum [mm/a]

Figure 11. Climate data of Holzkirchen

4.4. Used Calculation Models for Analysis

Two different calculation models are utilized for this analysis. One of them is the calculation model is specified in TS 825 Directive on the Thermal Insulation in Buildings [4]. This model is used for 1D and steady-state calculations. Another is WUFI Pro 5.3 developed by Künzel [5]. This model is used for 1D and transient calculations.

In this part, the calculation assumptions, calculation procedure, calculation steps with selected cases, calculation results of these models are explained.

4.4.1. Calculation Model Specified in TS 825

This method is used to examine the risk of condensation between the structural elements due to water vapor diffusion. Condensation within the structure is affected several factors that are the thickness of building materials, their resistance to heat transfer and water vapor diffusion, and the order of the materials, the temperature distribution within the building materials, climatic conditions.

This method, specified in TS 825 Directive on the Thermal Insulation in Buildings, is based on Glaser calculation model. There are some assumptions in this model. These are;

- Steady – state and 1 dimensional calculation
- Thermal and moisture transfer are evaluated independently of each other
- Only vapor diffusion is considered according to Fick’s law as moisture transfer
- Solely conduction is considered according to Fourier’s law as heat transfer
- Sorption and migration of the liquid water in the wall are not considered the calculation
- The initial moisture content of building materials is not considered
- The monthly mean temperature and relative humidity of internal and external environment are utilized in the calculation
- If the water partial vapor pressure is equal to saturated water vapor pressure on interstitial surfaces, condensation of water vapor occurs at this place.

The material properties and boundary conditions were explained, and then the calculation steps were explained. The material properties and boundary conditions are the key factor for the heat and moisture transfer in the building wall.

4.4.1.1. Material Properties

The used material properties are bulk density, porosity, specific heat capacity, thermal conductivity, diffusion resistance factor in this study. The constant material properties are used. These values are shown in Table 4. The materials that have similar properties with the materials in TS 825 were selected [4].

Table 4. Material Properties

Material		**Bulk Density (kg/m^3)**	**Porosity (m^3/m^3)**	**Specific Heat Capacity (J/kgK)**	**Thermal Conductivity (W/mK)**	**Diffusion Resistance Factor (-)**
Plastering	Cement Plastering	2000	0.3	850	1.2	25
	Lime Plastering	1600	0.33	850	0.7	12
Body Element	Concrete	2200	0.18	850	1.6	92
	Brick	1650	0.41	850	0.6	9.5
	Aerated Concrete	600	0.72	850	0.14	8.3
Insulation Material	Mineral Wool	60	0.95	850	0.04	1.3
	Extrude Polystyrene Foam	40	0.95	1500	0.03	100
	Expanded Polystyrene Foam	30	0.95	1500	0.04	50

4.4.1.2. Boundary Conditions

The mean monthly climate data were used in this calculation model. The boundary conditions are temperature and relative humidity of inside and outside for the calculation. With the studies, it is determined that the risk of condensation occurs most in Erzurum in our country. Therefore, for this thesis, climatic data of Holzkirchen were used. The climate data of Holzkirchen is like Erzurum data, but it is colder and more humid than Erzurum, as seen in Table 3.

The temperature and relative humidity of inside and outside in Holzkirchen are shown in Table 5.

Table 5. Temperature and Relative Humidity of Outside and Inside

Month	Outside Temperature (^oC)	Outside Relative Humidity (%)	Inside Temperature (^oC)	Inside Relative Humidity (%)
January	-6.22	88	20	65
February	-3.07	84		
March	-0.12	80		
April	7.31	78		
May	10.11	72		
June	16.10	71		
July	16.80	77		
August	14.47	83		
September	13.80	81		
October	2.62	84		
November	1.62	88		
December	-2.61	89		

4.4.1.3. Calculation Heat and Moisture Transport

Firstly, the main required properties of materials are shown in Table 6. They are thermal conductivity, thermal resistance, water vapor resistance factor, water vapor diffusion-equivalent air layer thickness. Then, the calculation scheme was explained, and each step was done with selected case.

- Required Material Properties

Some material properties are needed to analyze the interstitial condensation risk in the building external wall. These material properties are shown in Table 6.

Table 6. Required Properties of Material

Property	Symbol
Thermal conductivity	k
Thermal resistance	R
Diffusion resistance factor	μ
Water vapor diffusion-equivalent air layer thickness	s_d

Thermal Conductivity; is a measure of how well a material transfers heat. The thermal conductivity of a material can be defined as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature differences. The unit is W/mK.

Thermal Resistance; is calculated with thickness and thermal conductivity value of materials, described by the following equation:

$$R = \frac{d}{k} \tag{7}$$

Where;

d: Thickness of material (m)

k: Thermal conductivity (W/mK)

R: Thermal resistance (m^2K/W)

Thermal resistance values of interior and exterior space are specified as R_i = 0,25 m^2K/W and R_e = 0,04 m^2K/W in TS 825 Directive on the Thermal Insulation in Buildings for condensation calculations [4]

Water Vapor Diffusion Resistance Factor, μ-Value; the ratio of the diffusion coefficients of water vapor in air and in the building material and has therefore a simple interpretation: it is the factor by which the vapor diffusion in the material is impeded, as compared to diffusion in stagnant air. For very permeable materials, such as mineral wool, the μ-value is thus close to 1, whereas it increases for materials with greater diffusion resistance.

Water Vapor Diffusion-Equivalent Air Layer Thickness; is the thickness of a motionless air layer which has the same water vapor resistance as the material layer in question:

$$s_d = \mu * d \tag{8}$$

Where;

μ: Water vapor diffusion resistance factor (-)

d: Thickness of material (m)

S_d: Water Vapor Diffusion-Equivalent Air Layer Thickness (m)

- Calculation Scheme of Heat and Moisture Transport

1. Determination of material properties.
2. Calculation of cumulative water vapor diffusion-equivalent air layer thickness and cumulative thermal resistance.
3. Calculation of density of heat flow rate for each month.
4. Calculation of the temperature of each interlayer.
5. Determining the saturation vapor pressures at these points as a function of temperature. Also, calculation of partial water vapor pressure of inside and outside.
6. Creating a graphic composed saturation vapor pressures values of interlayers and partial water vapor pressure of inside and outside.
7. Determination of whether or condensation for each month
8. Estimating of the amount of condensed water in interlayer.
9. Controlling the evaporation of condensed water, determination of condensation risk.

First part of calculation is the determination of material properties. The thermal resistance, R, and the water vapor diffusion-equivalent air layer thickness, S_d, of each individual layer of the building element are calculated. The thermal resistance and the water vapor diffusion-equivalent air layer thickness from the outside to each interface n are calculated by the following equation:

$$R'_n = R_{se} + \sum_{j=1}^{n} R_j \tag{9}$$

$$S_{d,n} = \sum_{j=1}^{n} S_{d,j} \tag{10}$$

In second part, the cumulative thermal resistance and the water vapor diffusion-equivalent air layer thickness are given by following equation:

$$R'_T = R_{si} + \sum_{j=1}^{N} R_j + R_{se} \tag{11}$$

$$s'_{d,T} = \sum_{j=1}^{N} s_{d,j} \tag{12}$$

Table 7. Properties of Materials in Structure

	Layer Thickness d (m)	**Diffusion Resistance Factor μ (-)**	**Water vapour diffusion-equivalent air layer thickness S_d (m)**	**Water vapour diffusion-equivalent air layer thickness (cumulative) S_{dt} (m)**
R_i	-	-	-	-
Lime Plaster	0.02	12	0.24	0.24
XPS	0.06	100	6	6.24
Solid Brick	0.2	9.5	1.9	8.14
Cement Plaster	0.03	25	0.75	8.89
R_e	-	-	-	-

The brick with internal XPS insulation wall type was selected to be shown for the calculation process. The material properties of wall elements are shown in Table 7 and Table 8. The cumulative water vapor diffusion-equivalent air layer thickness and cumulative thermal resistance were calculated and be shown in Table 7 and Table 8.

Table 8. Properties of Materials in Structure

	Thermal conductivity *k* (W/mK)	**Thermal resistance R (m^2K/W)**	**Surface Thermal Resistance (cumulative) *Rt* (m^2K/W)**
Ri	-	0.04	0.04
Lime Plaster	1.2	0.02	0.06
XPS	0.03	2.00	2.06
Solid Brick	0.6	0.33	2.39
Cement Plaster	0.7	0.04	2.43
Re	-	0.25	2.68
			U= 0.37

Third part is the calculating heat flow rate for each month. Calculated values are shown in Table 9.

$\dot{q}$ is the rate of heat flow is given by:

$$\dot{q} = k * \frac{\Delta T}{R} \tag{13}$$

Where;

k: Thermal Conductivity

ΔT: Temperature Differences in ^{o}C

R: Thermal Resistance

$\dot{q}$: The rate of heat flow

Table 9. The Density of Heat Flow Rate Values for Each Month

Month	$\dot{q}$ **(W/m^2)**
January	9.77
February	8.60
March	7.50
April	4.73
May	3.68
June	1.45
July	1.19
August	2.06
September	2.31
October	6.48
November	6.85
December	8.43

Fourth part is calculation of the temperature of each interlayer, interior and exterior surface. Next part is the determining the saturation vapor pressures at these points as a function of temperature are given in Appendix C and partial water vapor pressure of inside and outside. The temperature and saturated water vapor pressure values in all interlayers were calculated for all months in a year. These values of January and February were selected to be shown. These values are shown in Table 10 and Table 11.

Table 10. Temperature and Saturated Water Vapor Pressure at Interlayers

	January		February	
	Temperature *(°C)*	**Pressure (Pa)**	**Temperature** *(°C)*	**Pressure (Pa)**
Outside	-6.22	375	-3.07	475
Outer Surface	-3.77	504	-0.92	657
1.Interlayer	-3.36	488	-0.55	636
2.Interlayer	-0.10	611	2.32	721
3.Interlayer	19.45	2252	19.51	2266
Interior Surface	19.61	2280	19.66	2280
Inside	20.00	2337	20.00	2337

- Partial Water Vapor Pressure

$$p = p_s * \varphi \qquad (14)$$

where;

p: Partial Water Vapor Pressure (Pa)

φ: Relative Humidity (-)

p_s: Saturated Water Vapor Pressure at 'θ' temperature (Pa)

Table 11. Partial Water Vapor Pressure in Pa of Inside and Outside

	January	**February**
P_d	329.30	398.66
P_i	1519.05	1519.05

The sixth part is that creating a wall section considering the water vapor diffusion-equivalent air layer thickness of the material. Then, the saturated water vapor pressures at the interlayers in the wall section are marked and connected with lines. The partial water vapor pressures of inside and outside are marked and connected with a line in the same wall section. It is determined whether or condensation in this building element by analyzing this graphic. If the vapor pressure surpasses the saturated water vapor pressure at any interlayer, it means that there is condensation in this interlayer.

The diffusion graph of brick with internal XPS insulation wall type is shown in Figure 12. The graphs were created for control in January. The graphs of other months for brick wall with internal XPS were in Appendix D. In 2nd interlayer between brick and XPS, the partial water vapor pressure higher than saturated water vapor pressure. This means, the water vapor condensation occurs in 2nd interlayer.

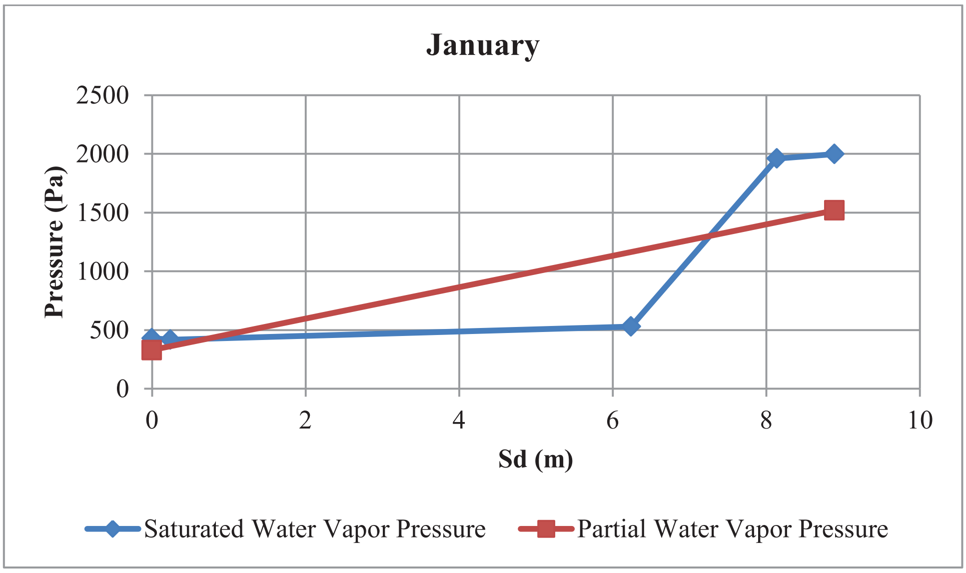


Figure 12. Diffusion Graph of Brick Wall with Internal XPS in January

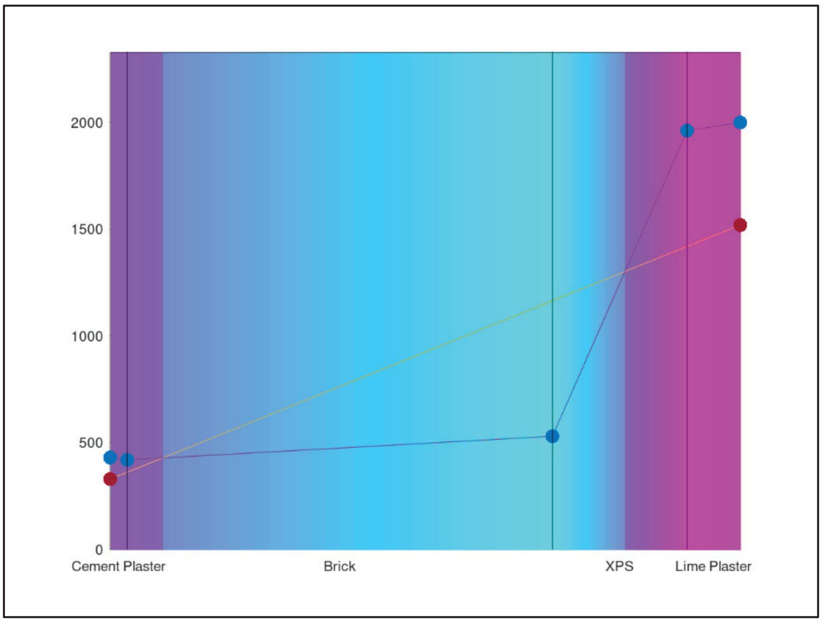


Figure 13. Condensation Control in Brick Wall with Internal XPS

The same graph was created with using code written in Octave [33]. This Figure 13 shows the saturation vapor pressures at each interlayer and the partial water vapor pressure of inside and outside. The figure shows the most and least condensation risk regions in the wall section. The sections consist of water vapor diffusion-equivalent air layer thickness of each material. The turquoise region represents the condensation region and the pink region represents the least condensation risk region in the building section.

The last part is calculation of amount of condensed water and control the evaporation of condensed water.

- Calculation of interstitial condensation amount

If the saturated water vapor pressure surpasses the partial water vapor pressure, there is a condensation. The starting month is the first month in which condensation begins, if condensation occurs anywhere in the building component during the year. The calculations start from the starting month by determining the temperature, water vapor saturation pressure and vapor distributions in the component. The accumulated mass of condensed water at the end of those months when condensation has occurred is compared with the total evaporation during the rest of the year.

Moisture transfer is assumed to be pure water vapor diffusion, described by the following equation:

$$g = \frac{\delta_0}{\mu} * \frac{\Delta p}{d} = \delta_0 * \frac{\Delta p}{s_d} \tag{15}$$

Where $\delta_0 = 2 * 10^{-10}$ kg/(m·s·Pa)

For condensation amount at one interlayer in the structure element,

$$g_{sw} = \frac{p_i - p_{sw}}{s'_{dt} - s'_{d,sw}} - \frac{p_{sw} - p_d}{s'_{d,sw}} \tag{16}$$

$$m_y = g * t \tag{17}$$

Where;

m_{y}: Amount (mass) of condensed and / or evaporated water

g: Amount (mass) of water condensing and / or evaporating in 1 second

t: 1-month time in seconds (86400 x 30)

For the brick with internal XPS insulation wall type, the condensation started in October as seen in Table 12. And the condensation continued till May. The amount of condensed water is 0.879 kg/m^2 at the end of April. The most condensation occurred in January as 0 176 kg/m^2. At the end of the year, the condensed water did not evaporate wholly. The amount of condensed water is 0.446 g/m^2. This situation may cause problems due to mold formation. The calculation results are denominated in kilogram (kg/m²) per square meter.

Table 12. The condensed water amount in Brick Wall with inner XPS

	$T_{outdoor}$ (^{0}C)	$RH_{outdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
October	2.62	84	0.102	0.102
November	1.62	88	0.116	0.218
December	-2.61	89	0.158	0.376
January	-6.22	88	0.177	0.553
February	-3.07	84	0.156	0.709
March	-0.12	80	0.130	0.839
April	7.31	78	0.042	0.881
May	10.11	72	-0.007	0.873
June	16.10	71	-0.121	0.752
July	16.80	77	-0.127	0.626
August	14.47	83	-0.071	0.555
September	13.80	81	-0.056	0.499

In this study, the effect of insulation material location on the condensation control in the exterior wall was analyzed. The Figure 14 represents the condensation control of brick with external XPS wall. The saturated water vapor pressure is higher than partial water vapor pressure at all interlayer in the wall. There is no interstitial condensation in the wall. So, this wall is suitable in terms of condensation risk.

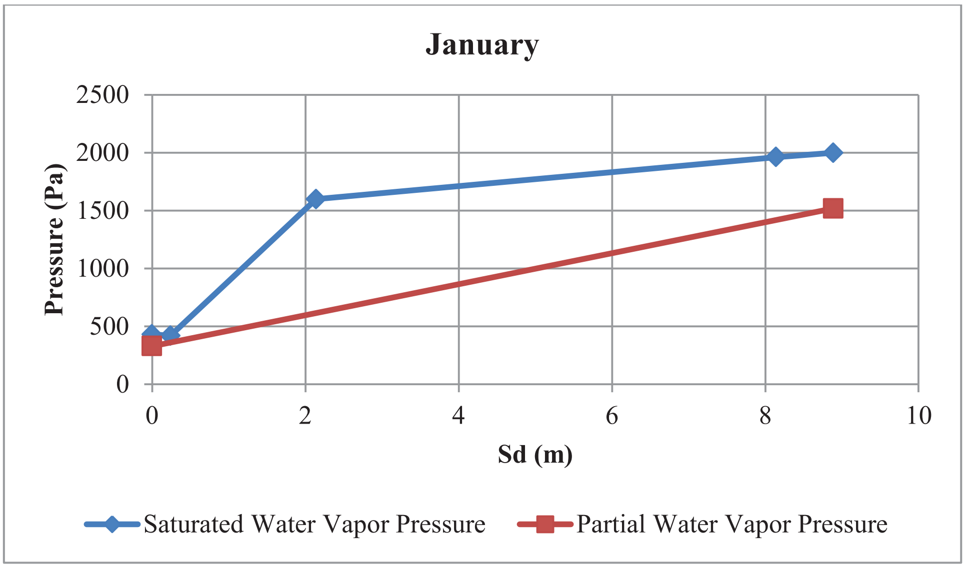


Figure 14. Diffusion Graph of Brick Wall with External XPS in January

The Figure 15 shows the condensation control graph created in Octave. There is no interstitial condensation in the wall. So, this wall is suitable in terms of condensation risk. The most condensation risk is in the 1st layer between cement plaster and XPS. This region is showed in blue color. Other control graphs of brick wall with external XPS insulation are given Appendix D. The tables of condensed water vapor amount of other brick wall types are given in Appendix E, F and G.

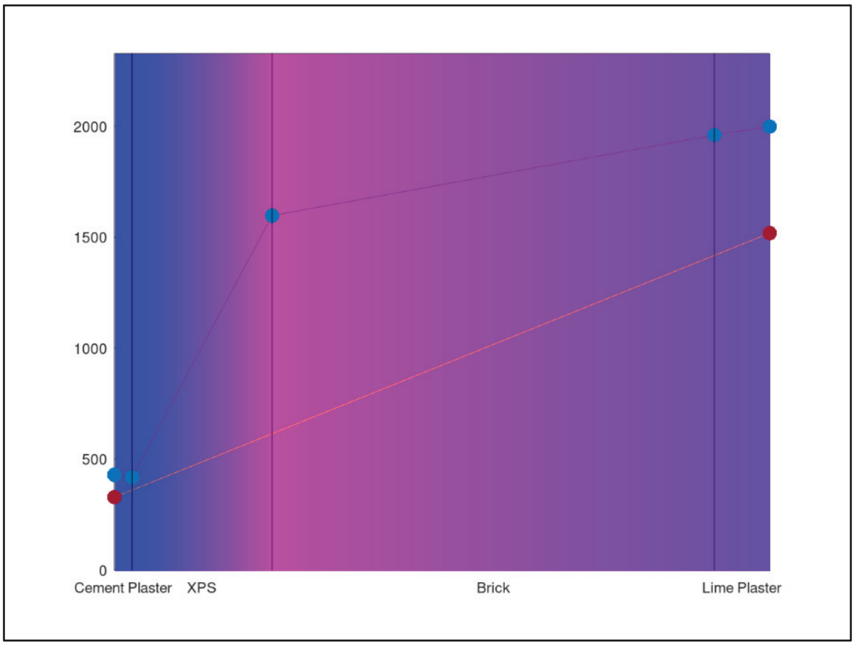


Figure 15. Condensation Control in Brick Wall with External XPS

- Concrete + EPS

In concrete wall with EPS internal insulation case, the partial water vapor pressure is higher than saturated water vapor pressure in 2nd interlayer between EPS and concrete according to Figure 16.

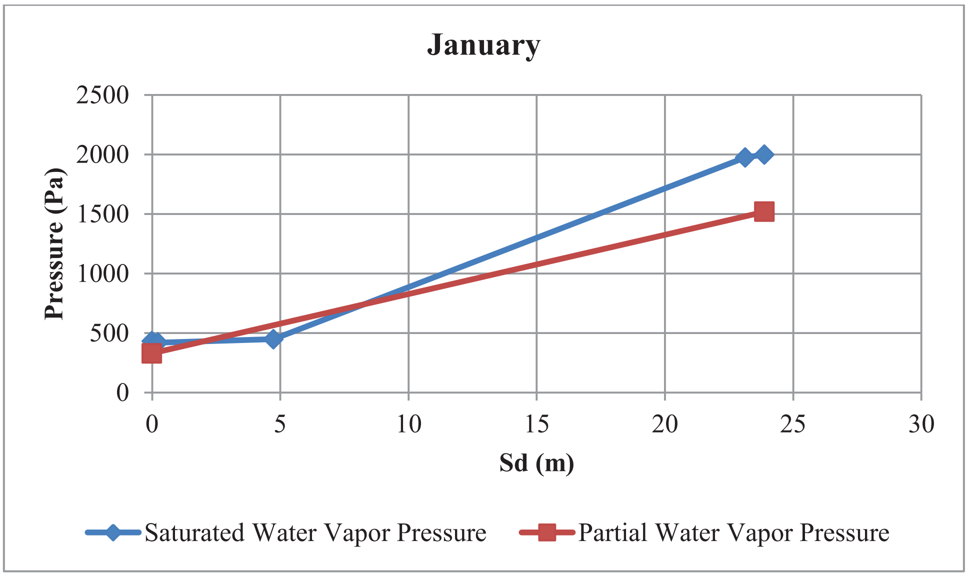


Figure 16. Diffusion Graph of Concrete Wall with Internal EPS in January

The Figure 17 shows the condensation control graph of concrete wall with internal EPS insulation created in Octave. The condensation occurs in 2nd interlayer between EPS and Concrete according to Figure 17. The turquoise region represents the condensation region and the pink region represents the least condensation risk region in the building section.

For the concrete with internal EPS insulation wall type, the condensation started in November as seen in Table 13. And the condensation continued till April. The amount of condensed water is 0.047 kg/m^2 at the end of March. The most condensation occurred in December as 0.017 kg/m^2. At the end of two months, the condensed water evaporated wholly. So, this wall type is suitable in terms of interstitial condensation risk. At the end of the year, the condensed water evaporated wholly. This wall type is suitable in terms of interstitial condensation in the wall. The condensation control graphs of other months are given Appendix H.

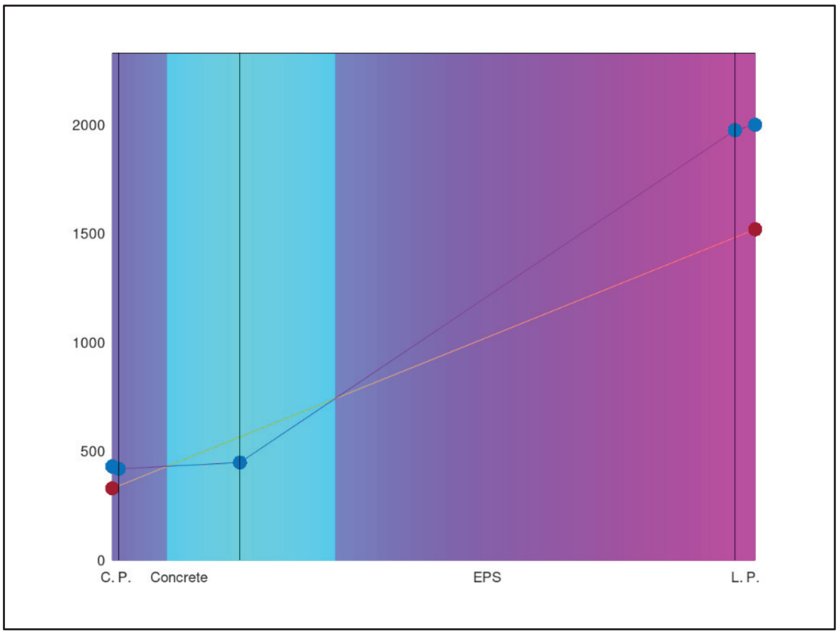


Figure 17. Condensation Control in Concrete Wall with Internal EPS

Table 13. The condensed water amount in Concrete Wall with Internal EPS

	$T_{outdoor}$ (^{0}C)	**$R_{Houtdoor}$ (%)**	**m_y (kg/m^2)**	**Σm_y (kg/m^2)**
November	1,62	88	0.004	0.004
December	-2,61	89	0.017	0.021
January	-6,22	88	0.016	0.037
February	-3,07	84	0.005	0.043
March	-0,12	80	0.004	0.047
April	7,31	78	-0.019	0.028
May	10,11	72	-0.039	-0.011
June	16,10	71	-0.069	-0.081
July	16,80	77	-0.065	-0.146
August	14,47	83	-0.040	-0.185
September	13,80	81	-0.031	-0.217
October	2,62	84	0.000	-0.217

The Figure 18 shows the condensation control of concrete wall with external EPS insulation. The saturated water vapor pressure is higher than partial water vapor pressure at all interlayer in the wall. There is no condensation at any interlayer in the wall. So, this wall type is suitable in terms of interstitial condensation risk.

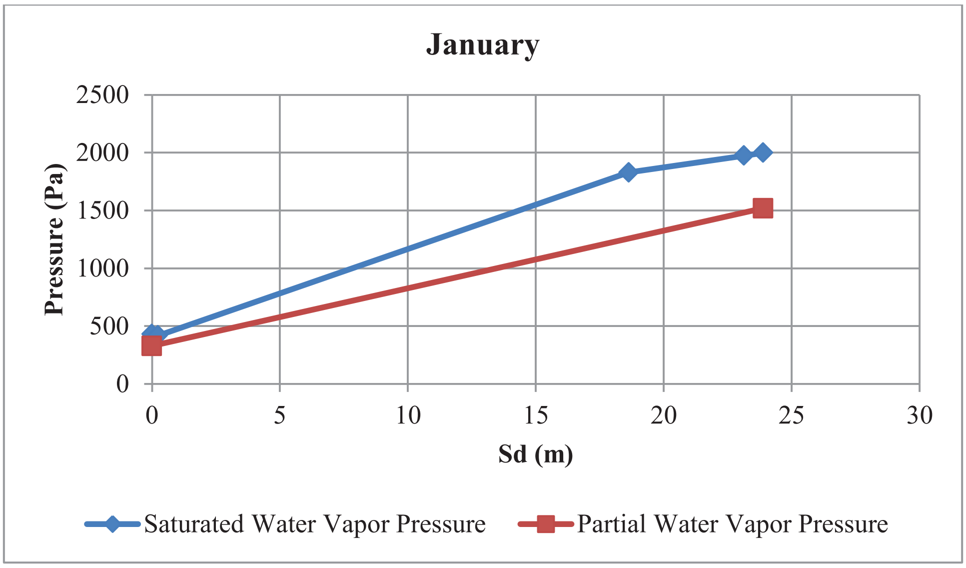


Figure 18. Diffusion Graph of Concrete Wall with External EPS

The Figure 19 shows the condensation control graph of concrete wall with external EPS insulation created in Octave. There is no interstitial condensation in the wall. So, this wall is suitable in terms of condensation risk. The most condensation risk is in the 1st layer between cement plaster and EPS. This region was showed in blue color. Other control graphs of concrete wall with external XPS insulation are given Appendix H. The tables of condensed water vapor amount of other brick wall types are given in Appendix I, J and K.

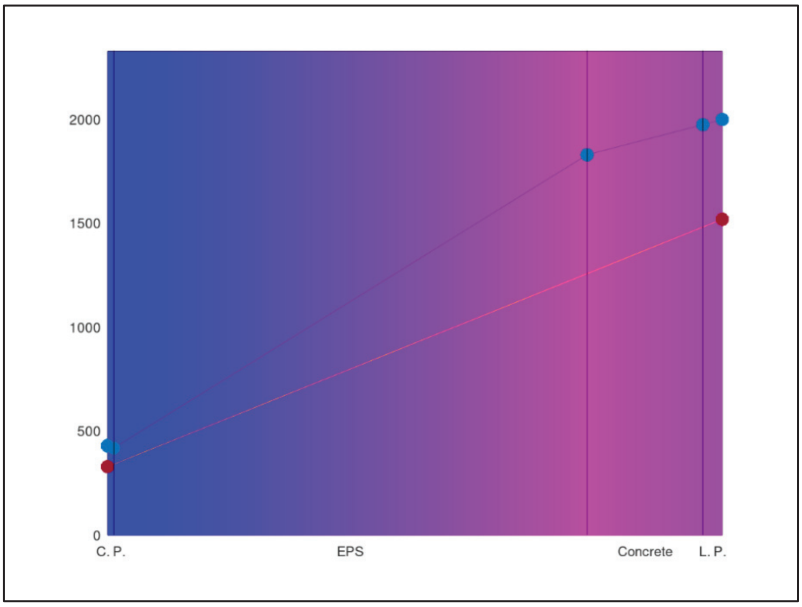


Figure 19. Condensation Control in Concrete Wall with External EPS

- Aerated Concrete + MW

Aerated concrete with MW insulation wall types were examined. In internal insulation case, the partial water vapor pressure is higher than saturated water vapor pressure in 1st interlayer between cement plaster and aerated concrete according to Figure 20.

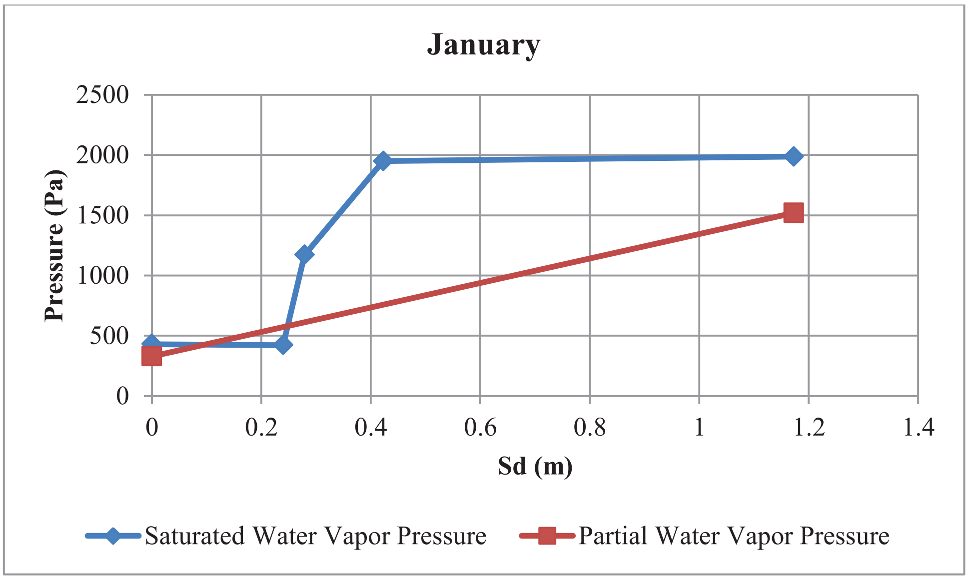


Figure 20. Diffusion Graph of Aerated Concrete Wall with Internal MW in January

The other condensation control graphs of aerated concrete wall with internal MW insulation are given in Appendix L. The Figure 21 shows the condensation control graph of aerated concrete wall with internal MW insulation created in Octave. The condensation occurs in 1st interlayer between cement plaster and aerated concrete according to Figure 21. The turquoise region represents the condensation region and the pink region represents the least condensation risk region in the building section.

For the aerated concrete with internal MW insulation wall type, the condensation started in October as seen in Table 14. And the condensation continued till April. The amount of condensed water is 1.697 kg/m^2 at the end of March. The most condensation occurred in December as 0.481 kg/m^2. At the end of three months, the condensed water evaporated wholly. So, this wall type is suitable in terms of interstitial condensation risk.

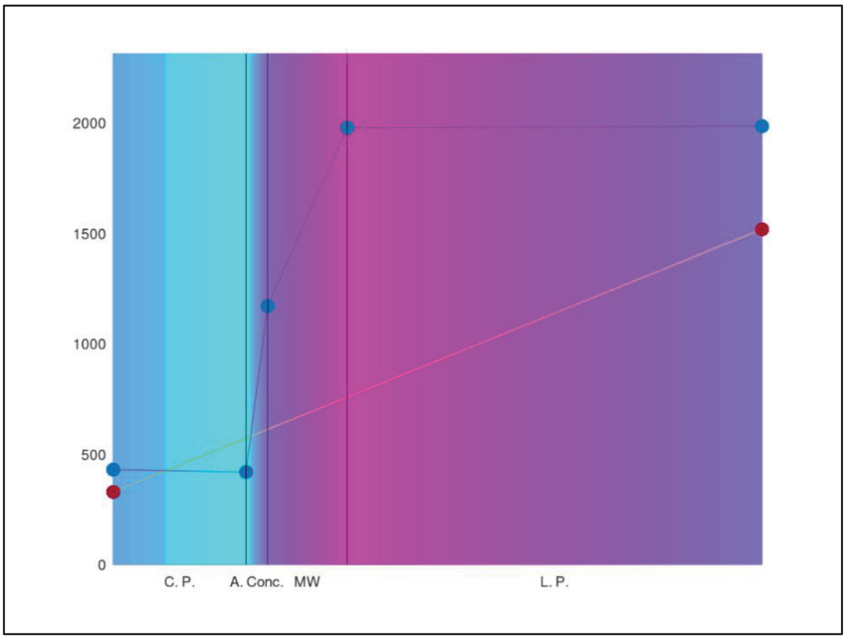


Figure 21. Condensation Control in Aerated Concrete with Internal MW

Table 14. The Condensed Water Amount in Aerated Concrete with Internal MW

	$T_{outdoor}$ (^0C)	$RH_{outdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
October	2.62	84	0.128	0.128
November	1.62	88	0.226	0.353
December	-2.61	89	0.481	0.834
January	-6.22	88	0.409	1.243
February	-3.07	84	0.241	1.485
March	-0.12	80	0.212	1.697
April	7.31	78	-0.266	1.431
May	10.11	72	-0.647	0.784
June	16.10	71	-1.349	-0.565
July	16.80	77	-1.162	-1.727
August	14.47	83	-0.726	-2.452
September	13.80	81	-0.533	-2.985

In external insulation case, the partial water vapor pressure is higher than saturated water vapor pressure in 1st interlayer between cement plaster and MW according to Figure 22.

The Figure 23 represents the condensation control graph of aerated concrete wall with internal MW insulation created in Octave. The condensation occurs in 1st interlayer between cement plaster and MW according to Figure 23. Also, the is condensation risk is in the 2nd layer between MW and aerated concrete. The blue region represents the condensation risk region. The turquoise region represents the condensation region and the pink region represents the least condensation risk region in the building section.

For the aerated concrete with external MW insulation wall type, the condensation started in October as seen in Table 15. And the condensation continued till April. The amount of condensed water is 1.697 kg/m^2 at the end of March. The most condensation occurred in December as 0.481 kg/m^2. At the end of three months, the condensed water evaporated wholly. So, this wall type is suitable in terms of interstitial condensation risk.

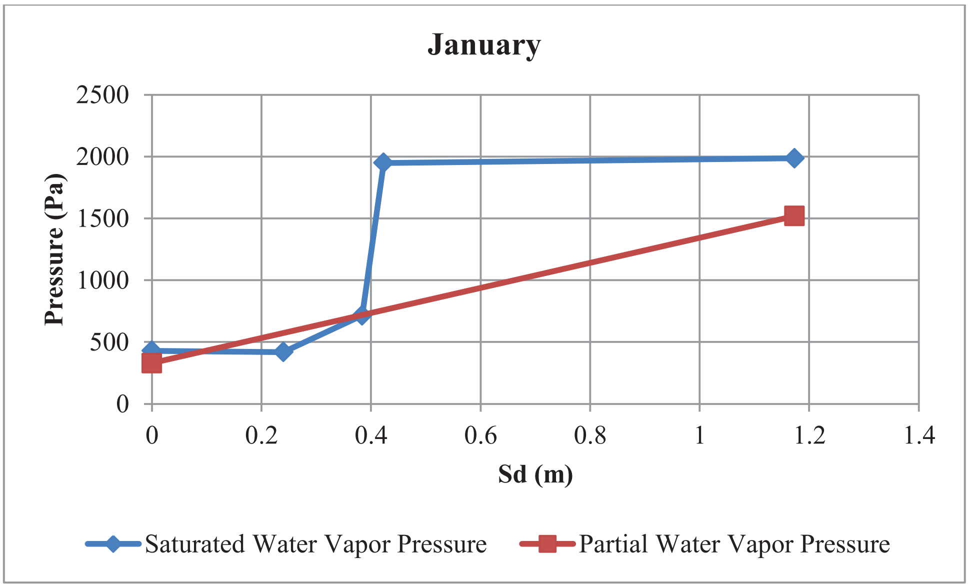


Figure 22. Diffusion Graph of Aerated Concrete with External MW in January

There is the same amount of condensed water vapor in aerated concrete with internal and external wall types. The difference between the two wall types is that there is a risk of condensation in 2nd interlayer on the external insulation wall type, while there is no such problem in 2nd interlayer on the internal insulation wall type. The aerated concrete with internal insulation wall type is more suitable in terms of condensation risk. Other control graphs of concrete wall with external XPS insulation are given Appendix L.

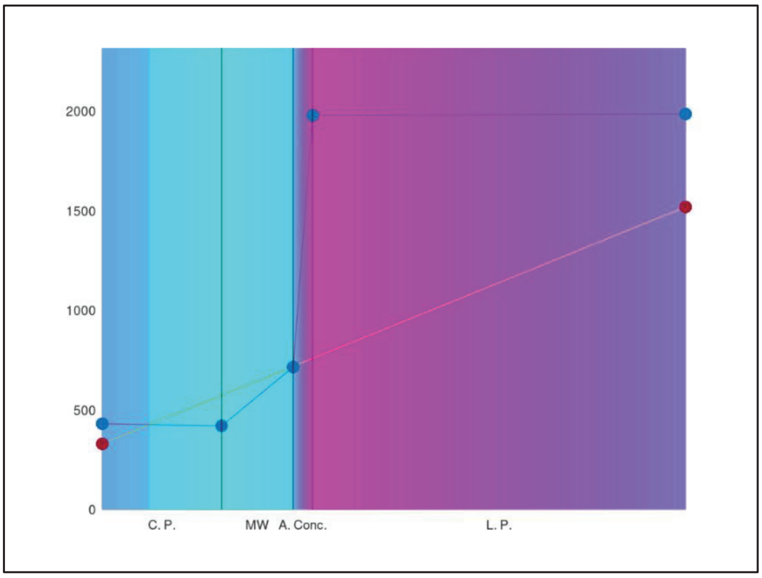


Figure 23. Condensation Region in Aerated Concrete Wall with External MW

The tables of condensed water vapor amount of other aerated concrete wall types are given in Appendix M, N and O.

Table 15. The condensed water amount in Aerated Concrete Wall with External MW

	$T_{outdoor}$ (^0C)	$RH_{outdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
October	2.62	84	0.128	0.128
November	1.62	88	0.226	0.353
December	-2.61	89	0.481	0.834
January	-6.22	88	0.409	1.243
February	-3.07	84	0.241	1.485
March	-0.12	80	0.212	1.697
April	7.31	78	-0.266	1.431
May	10.11	72	-0.647	0.784
June	16.10	71	-1.349	-0.565
July	16.80	77	-1.162	-1.727
August	14.47	83	-0.726	-2.452
September	13.80	81	-0.533	-2.985

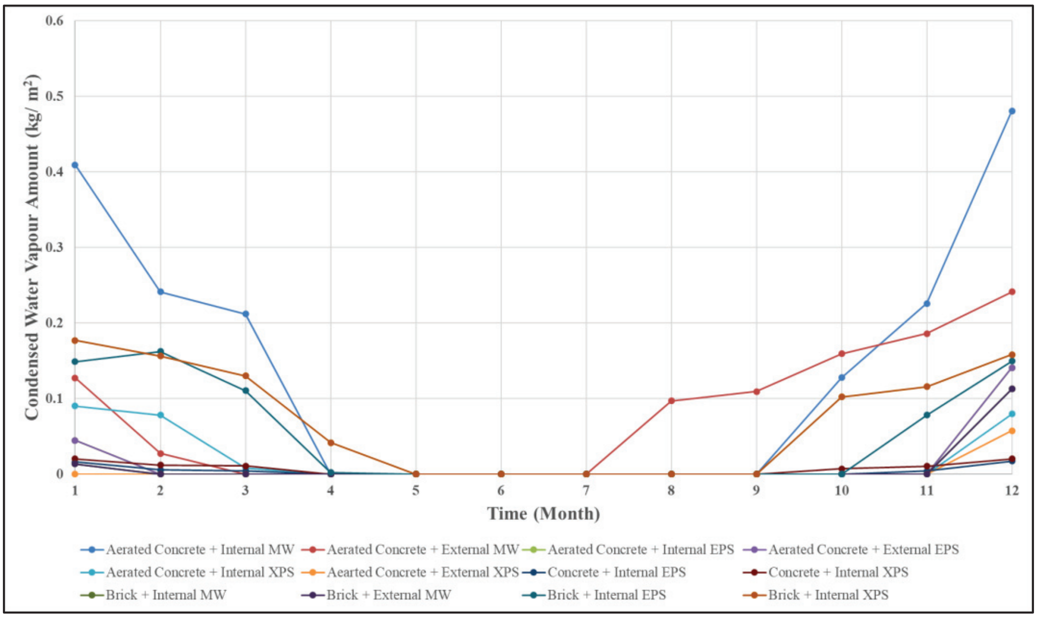


Figure 24. The Condensed Water Vapour Amount in the Wall Types for 1 year

The inferences obtained from Figure 24 and Appendices (D-O) are given below;

- Condensation usually takes place from September to April. The condensed water vapour generally evaporates in summer. The most condensed water vapour amount is in aerated concrete wall with internal in December and January in terms of the amount of condensation that occurs within 1 month. Aerated concrete wall with external MW gives the same results of aerated concrete wall with internal MW. The most condensed water vapour amount is in brick wall with internal XPS at the end of in a year. The condensation takes place from June to May in brick wall with internal XPS.
- Condensation takes place in all aerated concrete wall types. The condensed water vapour in all types of the aerated concrete wall except non-insulated type evaporates completely at the end of a year. So, aerated concrete wall types that are with insulation are suitable in terms of interstitial condensation.
- Condensation does not take place in concrete wall types that are with external insulations and internal MW. The condensed water vapour in concrete wall types that are with internal XPS and EPS evaporate completely at the end of a year. So, all concrete wall types that are with insulations do not pose a problem in terms of interstitial condensation.

- Condensation occurs in all brick wall types that are with internal insulations, external MW and without insulation. The condensed water vapour in all types of the brick wall except non-insulated type and internal XPS evaporates completely at the end of a year. So, types of brick wall those are with insulation except internal XPS are suitable in terms of interstitial condensation.
- All wall types that are without insulations and brick wall with internal XPS pose a problem in terms of interstitial condensation.

4.4.2. Transient Calculation Model- WUFI Pro 5.3

WUFI Pro 5.3 which is a windows-based program for the hygrothermal analysis of building envelope constructions is selected. WUFI [5] simulation model which is a transient heat and mass transfer model is designed, developed and discussed in the doctoral thesis of Künzel [5]. The heat and moisture distributions for a wide range of building material classes and climatic conditions were examined by using WUFI model. The heat and moisture distributions for a wide range of building material classes and climatic conditions were examined by using WUFI model.

Thermal conduction, enthalpy flows through moisture movement with phase change, short-wave solar radiation and nighttime long-wave radiation cooling are regarded in the calculation of heat transport by WUFI [5]. Moisture transfer mechanism are considered in WUFI as two parts which are vapor transport mechanism is consisted of vapor and solution diffusion, and liquid transport mechanism is consisted of capillary conduction and surface diffusion.

WUFI needs some data to perform the calculations. WUFI needs material data, climate data, surface transfer coefficients and initial conditions.

$$\frac{\partial w}{\partial \varphi}.\frac{\partial \varphi}{\partial t} = \nabla.(D_{\varphi}\nabla\varphi + \partial_{p}\nabla(\varphi\, p_{sat}) \tag{18}$$

$$\frac{\partial H}{\partial T}.\frac{\partial T}{\partial t} = \nabla.(k\nabla T + h_{v}\nabla(\delta_{p}\nabla(\varphi\, p_{sat}) \tag{19}$$

where;

φ : Relative humidity

t : Time, s

T : Temperature, ^{o}C

c : Specific heat, J/kgK

w : Moisture content, kg

p_{sat} : Saturation vapor pressure, Pa

k : thermal conductivity, W/ mK

H : total enthalpy, J/m^3

D_{φ} : liquid conduction coefficient, kg/ ms

δ_p : vapor permeability, kg/ msPa

h_v : latent heat of phase change, J/kg

The terms of on the left-hand side of the Equation 18 and 19 are store terms. Besides the flux terms on the right-hand side depend on heat and moisture. An implicit finite volume scheme is used to solve the coupled transfer equations, numerically. Calculated temperature and moisture distributions and the related fluxes for each time step are shown the resulting output.

The model gives the results by three types that are courses, profiles and film.
The following quantities are given as courses:

- The heat flux densities through the interior and exterior surface, respectively,
- The temperature and relative humidity values at selected monitoring positions,
- The mean moisture content of each layer and the total moisture content of the entire building component.

The following quantities are given as profiles:

- The temperature across the building component,
- The relative humidity across the building component,
- The moisture content across the building component.

And a film contains the profiles of all-time steps.

- Calculation Procedure

The composition of the examined building component, its orientation, and inclination, along with the initial conditions and the time period of interest are essential data for the calculation. The attached database enables the selection material parameters and climatic conditions. The moisture and energy balance equations must be solved by Starting from the initial temperature and water content distributions in the component for all time steps of the calculation period. This process of calculation is shown Figure 25.

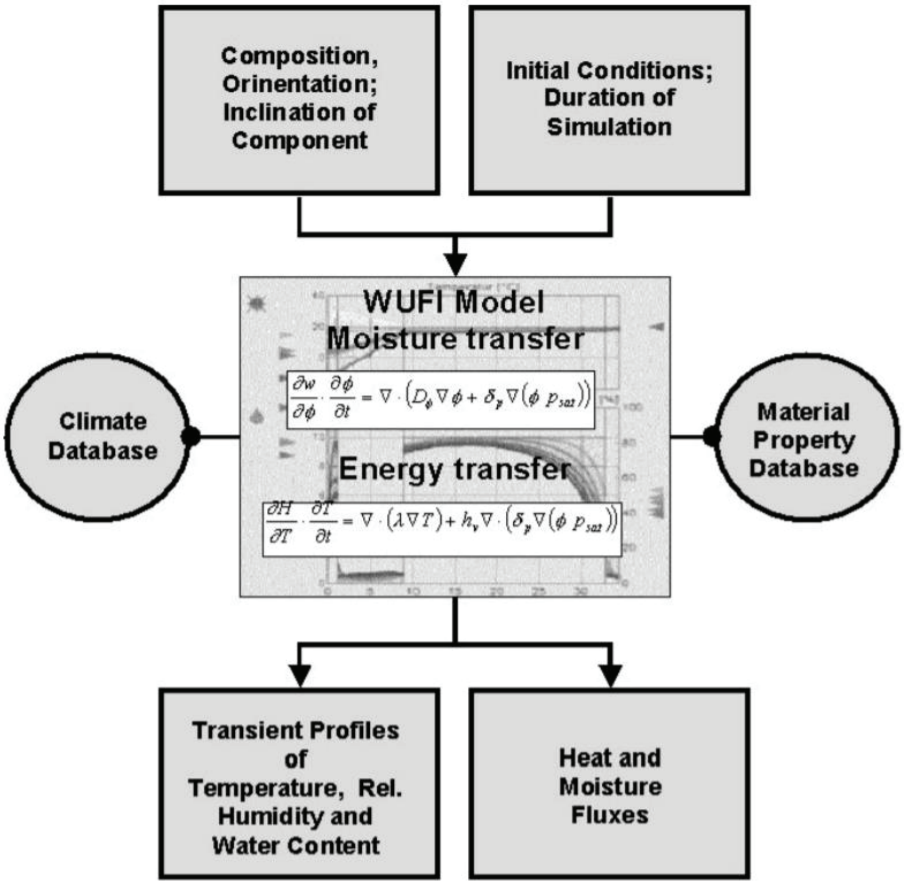


Figure 25. The Calculation Process Diagram of WUFI Model (Source: Künzel, H. M. *Simultaneous Heat and Moisture Transport in Building Components One- and Two-Dimensional Calculation Using Simple Parameters* .; 1995)

4.4.2.1. Material Properties

The simulation results reflect the actual situation equally as using the actual input data. Inability to access real data of material properties is main problem for simulation programs. Material database of WUFI includes a full range of materials commonly used in North America. Bulk density (kg/m3), porosity (m^3/m^3), specific heat capacity (J/kgK), thermal conductivity (W/mK), and water vapor diffusion resistance factor (-) are primary required properties. Also, moisture storage function and liquid transport are should be added if desired hygroscopic absorptive and capillarity. These properties are shown in Table 16.

WUFI Pro enables the adjustment of the thickness and position of the material within the structure. The brick with internal XPS insulation is selected to explain calculation process. The wall section and material properties are shown Figure 26-34.

Table 16. Material Properties of the Elements within the Wall

Material		**Bulk Density (kg/m^3)**	**Porosity (m^3/m^3)**	**Specific Heat Capacity (J/kgK)**	**Thermal Conductiviy (W/mK)**	**Diffusion Resistance Factor (-)**
Plastering	Cement Plastering	2000	0.3	850	1.2	25
	Lime Plastering	1600	0.33	850	0.7	12
Body Element	Concrete	2200	0.18	850	1.6	92
	Brick	1650	0.41	850	0.6	9.5
	Aerated Concrete	600	0.72	850	0.14	8.3
Insulation Material	Mineral Wool	60	0.95	850	0.04	1.3
	Extrude Polystyrene Foam	40	0.95	1500	0.03	100
	Expanded Polystyrene Foam	30	0.95	1500	0.04	50

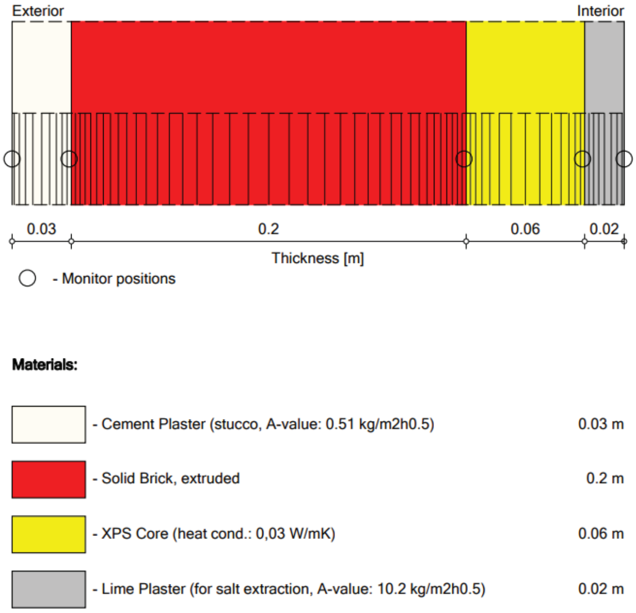
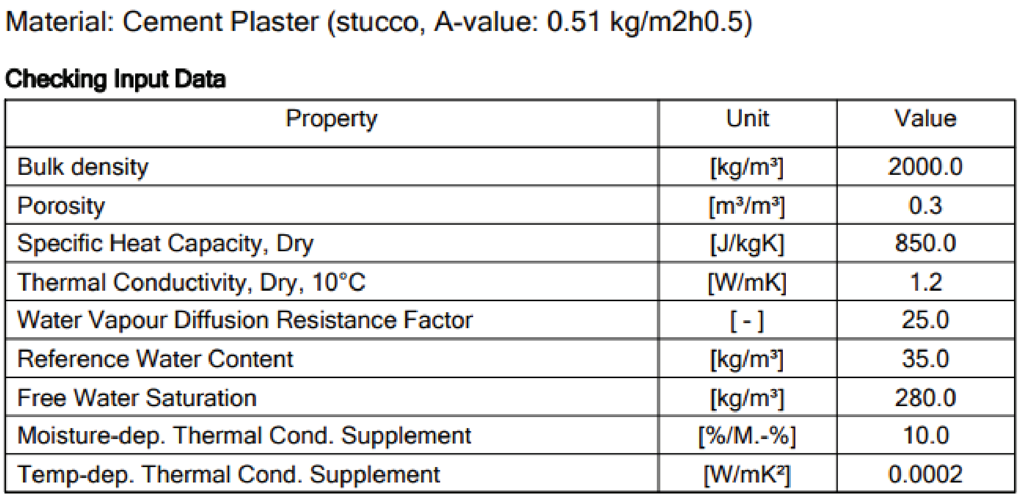


Figure 26. The Wall Section of Brick Wall with Internal XPS Insulation



Material: Cement Plaster (stucco, A-value: 0.51 kg/m2h0.5)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	2000.0
Porosity	[m³/m³]	0.3
Specific Heat Capacity, Dry	[J/kgK]	850.0
Thermal Conductivity, Dry, 10°C	[W/mK]	1.2
Water Vapour Diffusion Resistance Factor	[-]	25.0
Reference Water Content	[kg/m³]	35.0
Free Water Saturation	[kg/m³]	280.0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	10.0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 27. Material Properties of Cement Plaster

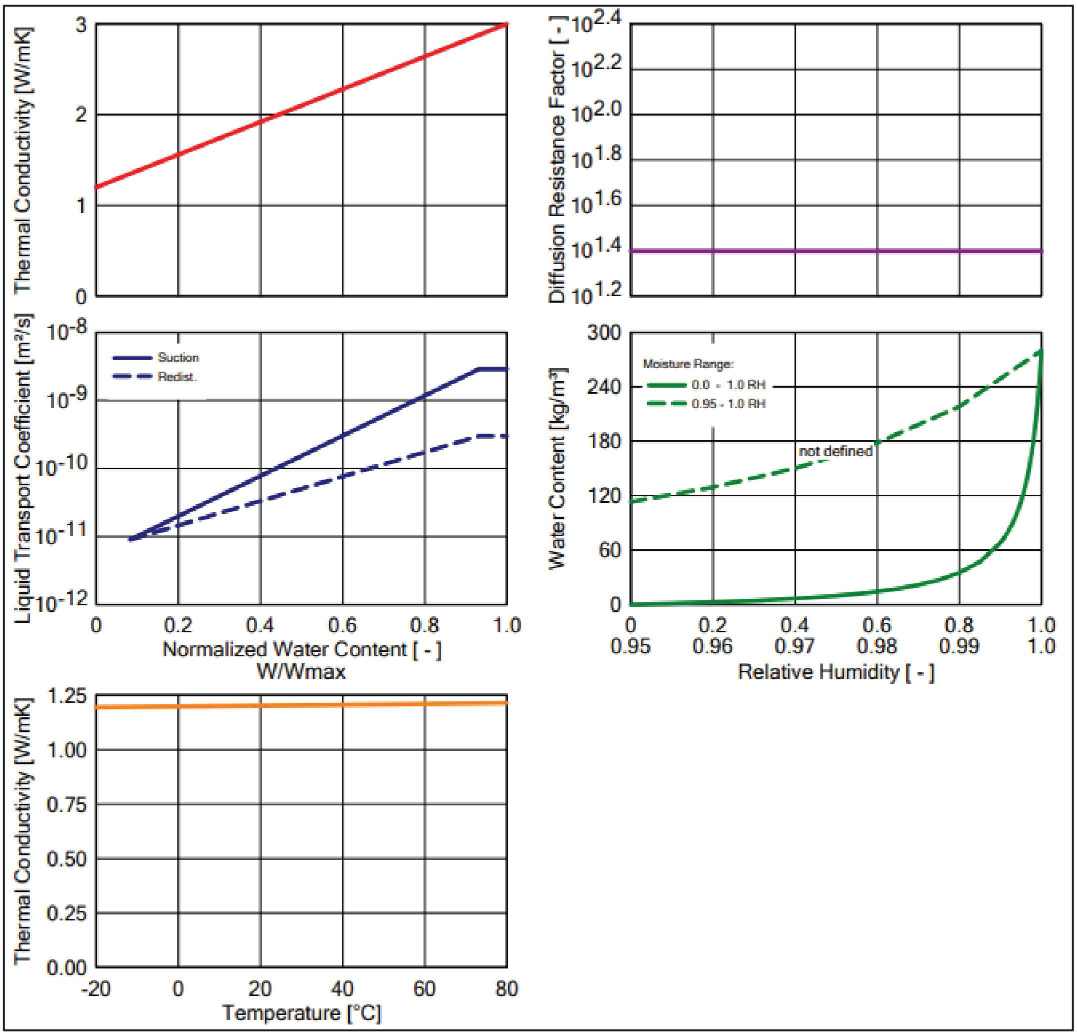


Figure 28. Change of Properties of Cement Plaster with Heat and Moisture Effect

Material: Solid Brick, extruded

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1650.0
Porosity	[m³/m³]	0.41
Specific Heat Capacity, Dry	[J/kgK]	850.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.6
Water Vapour Diffusion Resistance Factor	[-]	9.5
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	15.0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 29. Material Properties of Solid Brick

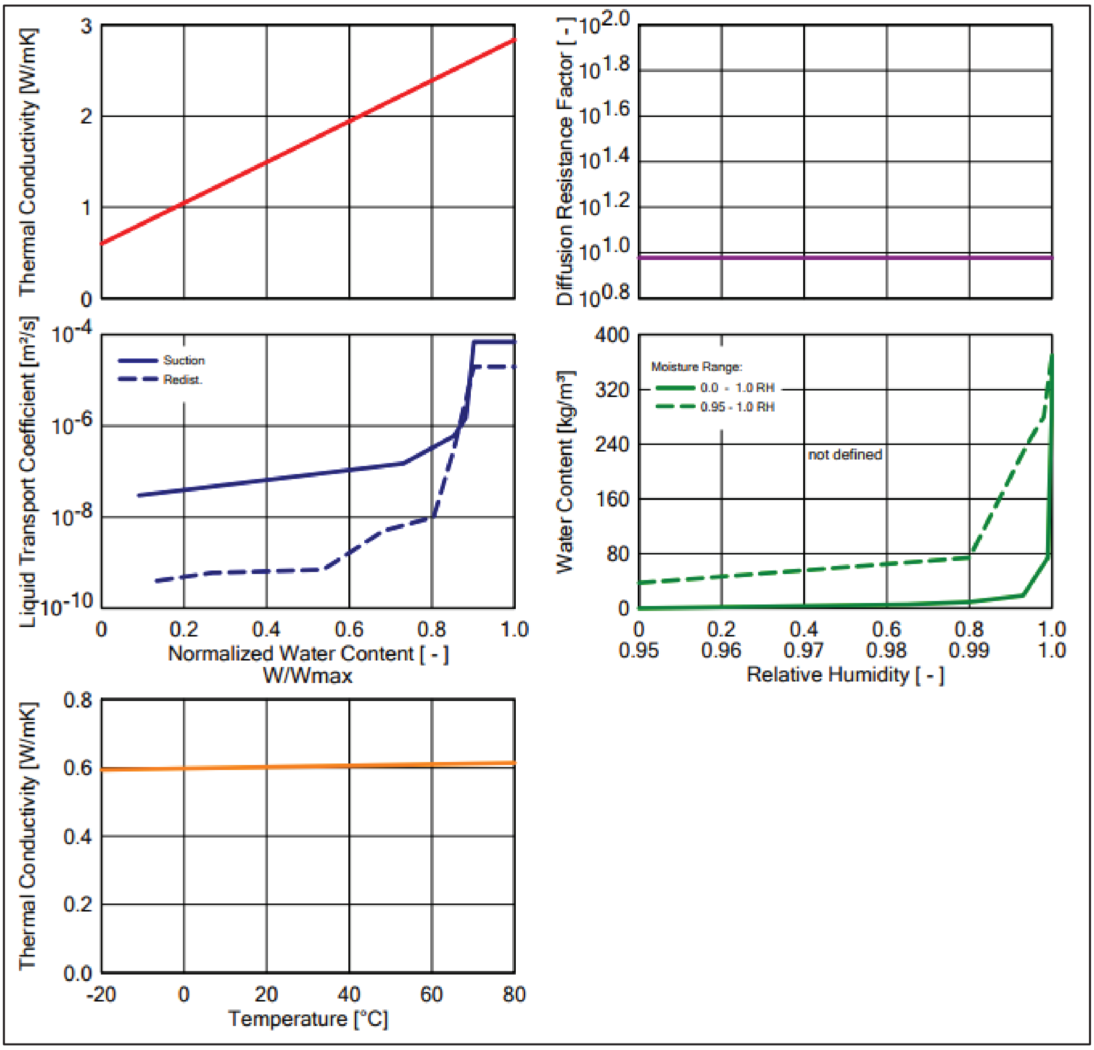
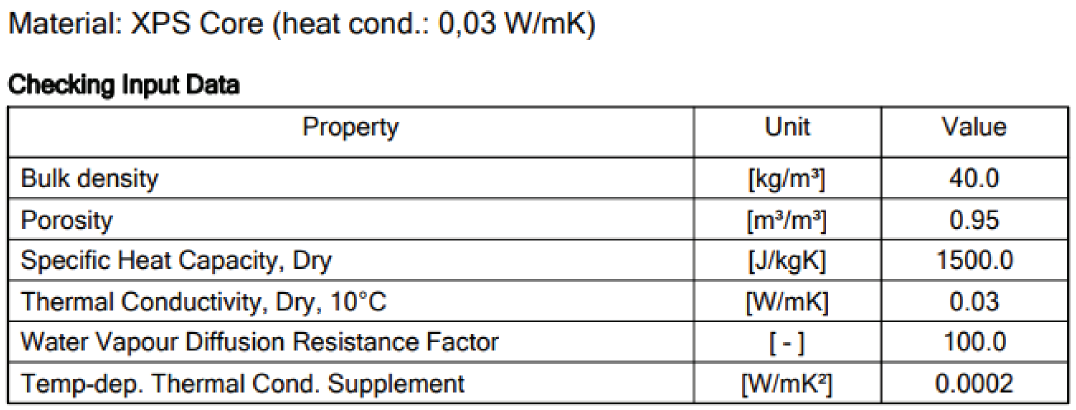


Figure 30. Change of Properties of Solid Brick with Heat and Moisture Effect



Material: XPS Core (heat cond.: 0,03 W/mK)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	40.0
Porosity	[m³/m³]	0.95
Specific Heat Capacity, Dry	[J/kgK]	1500.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.03
Water Vapour Diffusion Resistance Factor	[-]	100.0
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 31. Material Properties of XPS

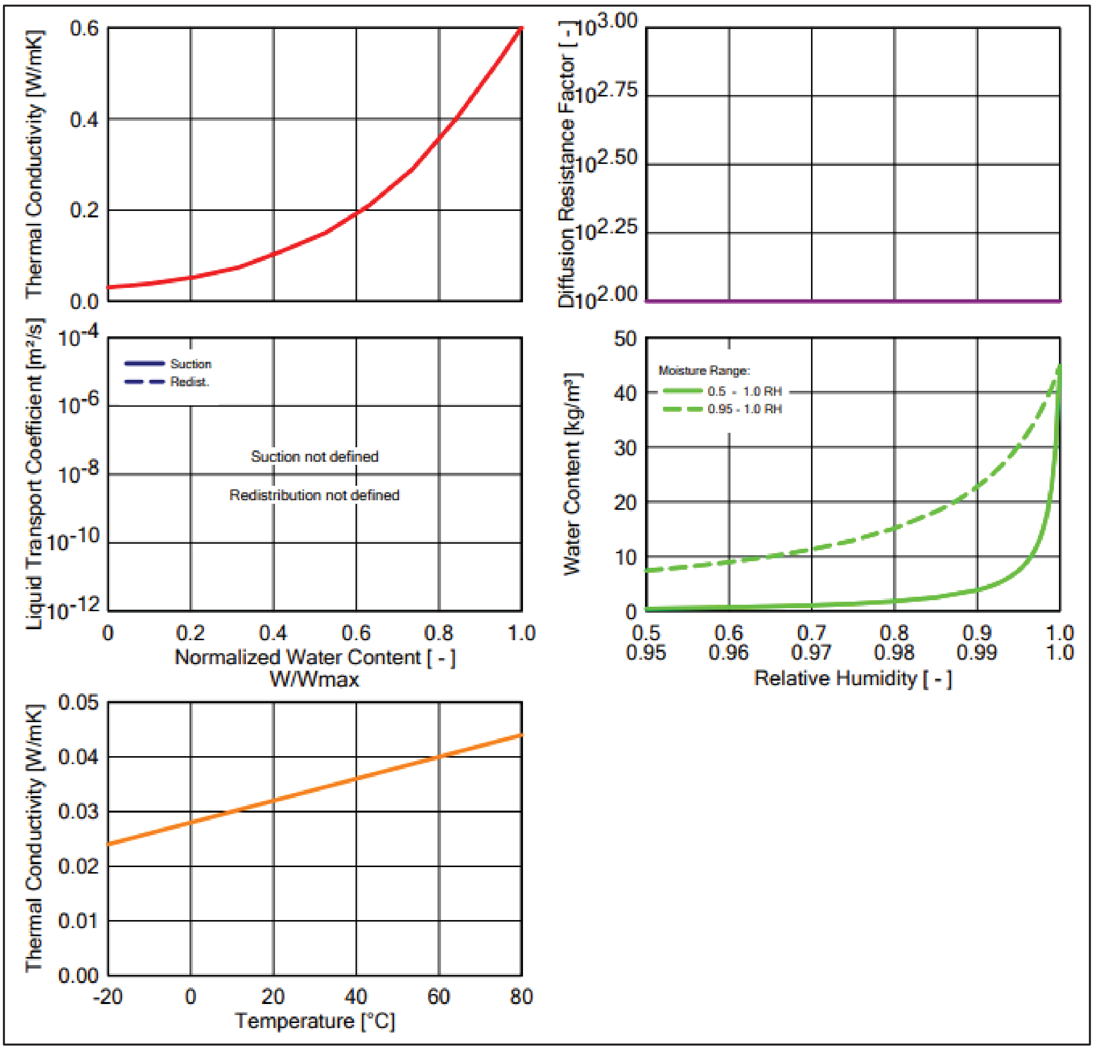


Figure 32. Change of Properties of XPS with Heat and Moisture Effect

Material: Lime Plaster (for salt extraction, A-value: 10.2 kg/m2h0.5)

Checking Input Data

Property	Unit	Value
Bulk density	[kg/m³]	1600.0
Porosity	[m³/m³]	0.33
Specific Heat Capacity, Dry	[J/kgK]	850.0
Thermal Conductivity, Dry, 10°C	[W/mK]	0.7
Water Vapour Diffusion Resistance Factor	[-]	12.0
Moisture-dep. Thermal Cond. Supplement	[%/M.-%]	3.7
Temp-dep. Thermal Cond. Supplement	[W/mK²]	0.0002

Figure 33. Properties of Lime Plaster

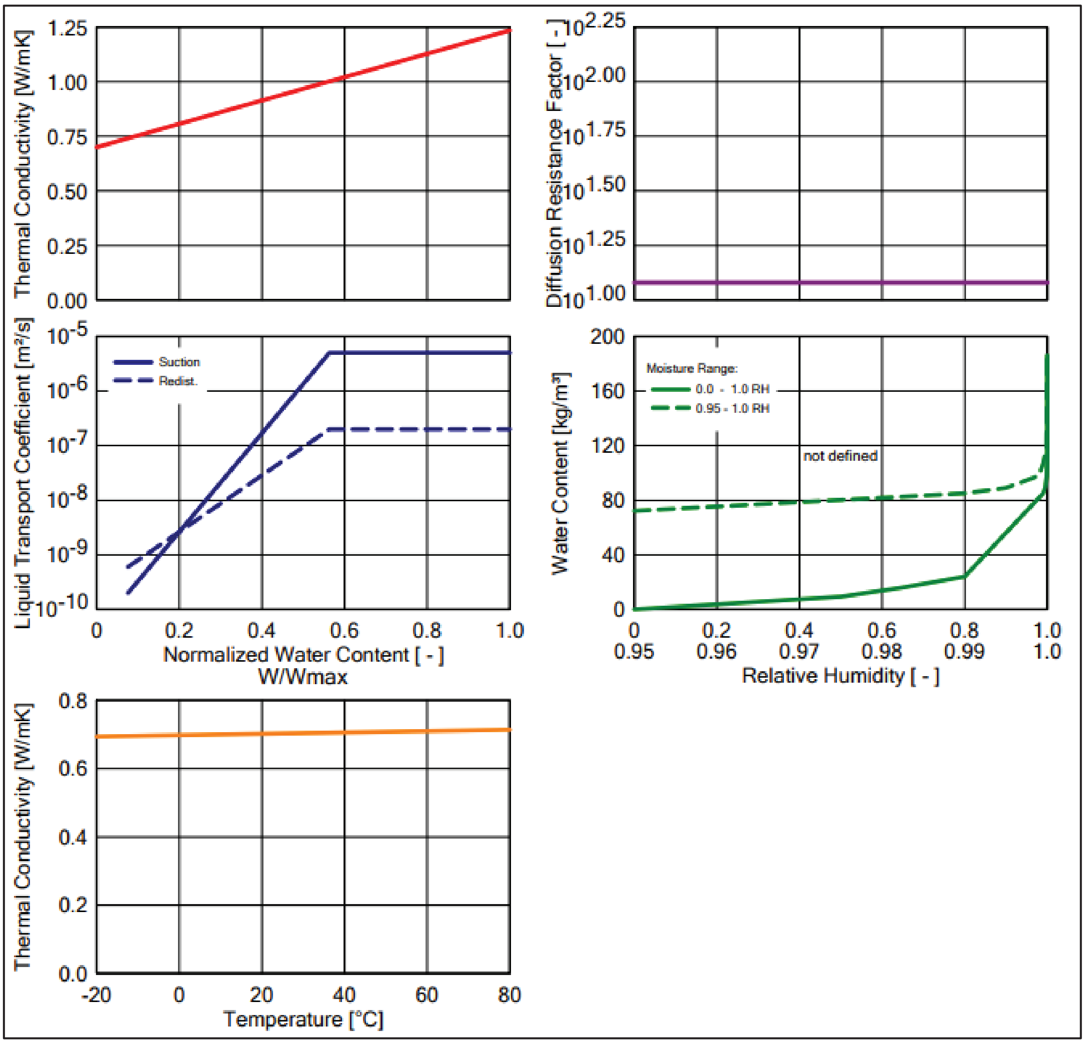


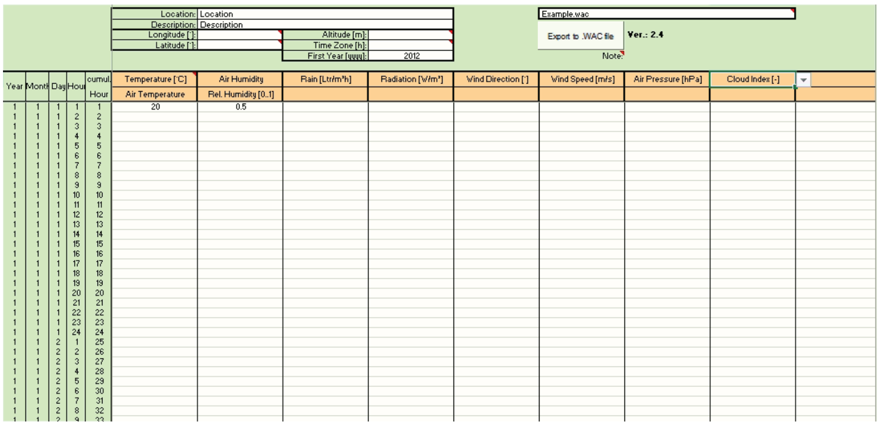
Figure 34. Change of Properties of Lime Plaster with Heat and Moisture Effect

4.4.2.2. Boundary Conditions

- The orientation of wall is north.
- The inclination of wall is 90°.
- The surface thermal resistance values of interior and exterior space are specified as Ri = 0.25 m^2K/W and Re = 0.04 m^2K/W in TS 825 Directive on the Thermal Insulation in Buildings for condensation calculations.
- The initial temperature and moisture in content is a constant across component. The initial temperature is 20 °C. The initial relative humidity is 80%.
- The calculation period is accepted 5 years. Starting date is accepted 1st of June.

4.4.2.3. Climate Data

WUFI Pro determines the hygrothermal performance of building components under real climate conditions. Climate data using the calculation is a sinusoidal curve depending on measured climate value. The computer model requires hourly weather data such as temperature, relative humidity, wind speed and orientation, driving rain, and solar radiation are employed in the hygrothermal calculations. WUFI database includes real-time climate data of cities in America, Japan and Europe. Data which are hourly dry-bulb, temperature, solar radiation, humidity, and wind speed and direction can be contributed input as a climate file with wac. extension based on excel program for other cities which are not in WUFI database. The sample wac. file is shown in Figure 35.



Location: Location
Description: Description
Longitude [°]:
Latitude [°]:
Altitude [m]:
Time Zone [h]:
First Year [yyyy]: 2012

Year	Month	Day	Hour	cumul. Hour	Temperature [°C] Air Temperature	Air Humidity Rel. Humidity [0..1]	Rain [Ltr/m²h]	Radiation [W/m²]	Wind Direction [°]	Wind Speed [m/s]	Air Pressure [hPa]	Cloud Index [-]
1	1	1	1	1	20	0.5						
1	1	1	2	2								
1	1	1	3	3								
1	1	1	4	4								
1	1	1	5	5								
1	1	1	6	6								
1	1	1	7	7								
1	1	1	8	8								
1	1	1	9	9								
1	1	1	10	10								
1	1	1	11	11								
1	1	1	12	12								
1	1	1	13	13								
1	1	1	14	14								
1	1	1	15	15								
1	1	1	16	16								
1	1	1	17	17								
1	1	1	18	18								
1	1	1	19	19								
1	1	1	20	20								
1	1	1	21	21								
1	1	1	22	22								
1	1	1	23	23								
1	1	1	24	24								
1	1	2	1	25								
1	1	2	2	26								
1	1	2	3	27								
1	1	2	4	28								
1	1	2	5	29								
1	1	2	6	30								
1	1	2	7	31								
1	1	2	8	32								
1	1	2	9	33								

Figure 35. Example wac. File

Holzkirchen is a market town in Bavaria, Germany. The average temperature in Holzkirchen is 6.6°C. The maximum temperature is 32.1°C. The minimum temperature is -20.1°C. The average relative humidity is 81%. The maximum relative humidity is 98% and the minimum relative humidity is 24%. The average wind speed is 2.33 m/s. The normal rain sum is 1185 mm/a. The rain mostly affects the west direction. The climate data of Holzkirchen are shown in Figure 36 and Figure 37. The climate analysis is shown in Figure 38.

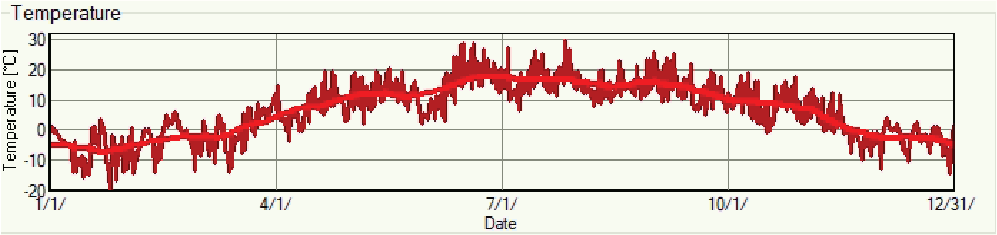


Figure 36. Outdoor Temperature

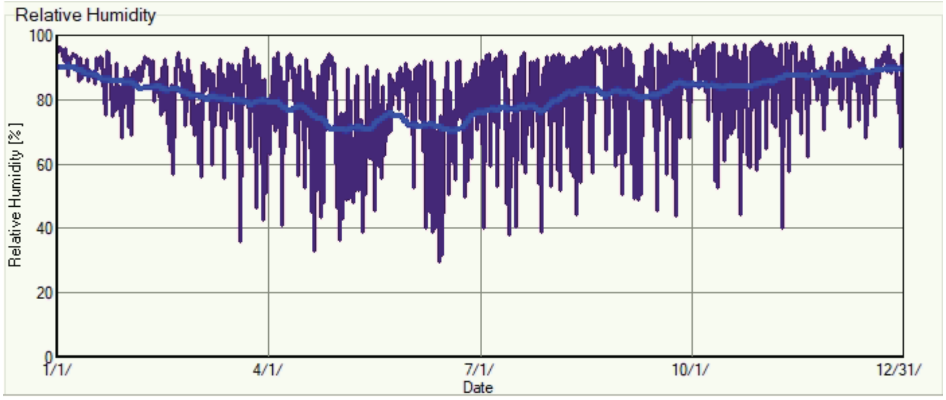


Figure 37. Outdoor Relative Humidity

The relative humidity and temperature data of interior space can be selected by using EN 13788 [34] and ASHRAE 160P [35] standards. Indoor humidity level is specified in the selected standard according to function of building.

EN 13788 [34] is selected for the analysis. The indoor temperature is constant and 20 °C. The indoor relative humidity is constant and 65% as shown in Figure 39 and 40.

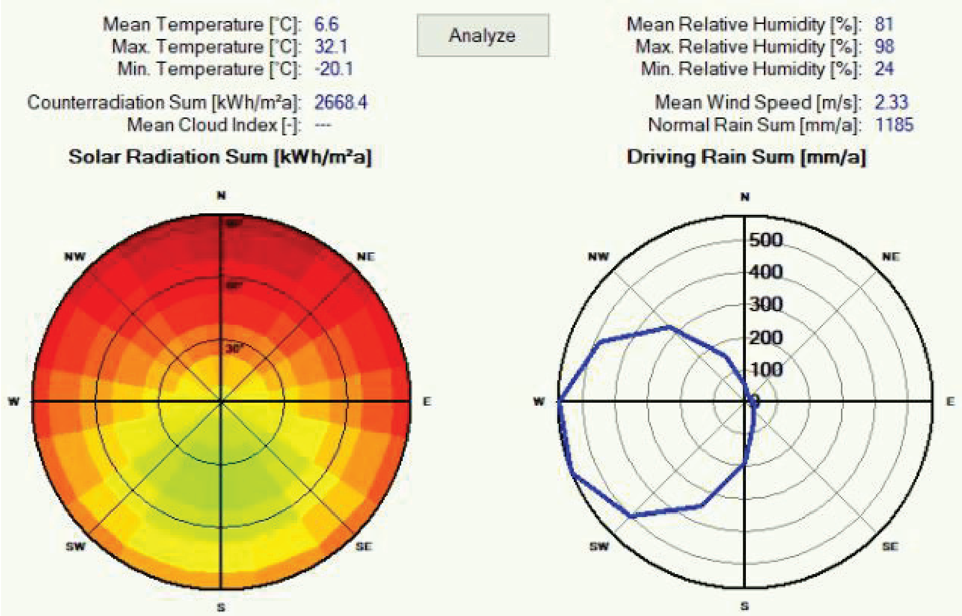

Mean Temperature [°C]: 6.6
Max. Temperature [°C]: 32.1
Min. Temperature [°C]: -20.1
Counterradiation Sum [kWh/m²a]: 2668.4
Mean Cloud Index [-]: ---
Mean Relative Humidity [%]: 81
Max. Relative Humidity [%]: 98
Min. Relative Humidity [%]: 24
Mean Wind Speed [m/s]: 2.33
Normal Rain Sum [mm/a]: 1185

Figure 38. Climate Analysis of Holzkirchen

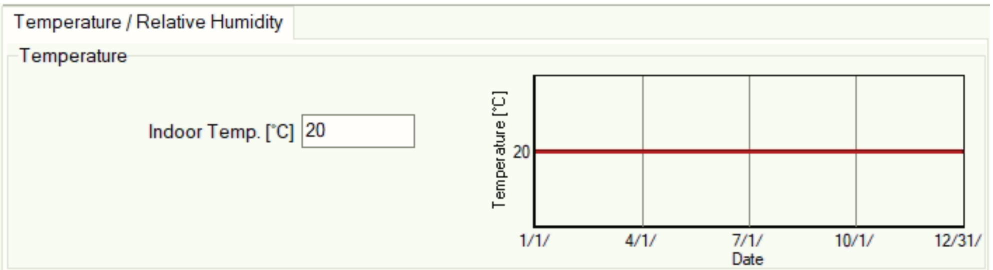

Indoor Temp. [°C] 20

Figure 39. Indoor Temperature

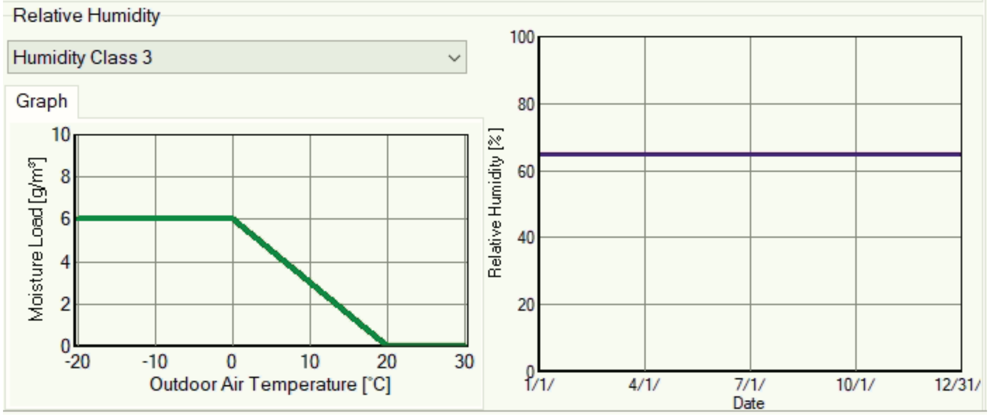

Humidity Class 3

Figure 40. Indoor Relative Humidity

4.4.2.4. Analyzing Heat and Moisture Transfer

In the simulation program, two options for mode of calculation. The program offers selection one of them or both. There are:

1. Heat Transport Calculation
2. Moisture Transport Calculation

Also, there are two options for thermal conductivity in the simulation program. There are:

1. Use Temperature and Moisture Dependency
2. Use Constant Design Value

The analysis was done in four different hygrothermal special options presented in the simulation program. These options are:

1. Excluding Capillary Conduction
2. Excluding Latent of Heat Evaporation
3. Excluding Temperature Dependency in Latent Heat of Evaporation
4. Excluding Latent Heat of Fusion

In this study, analyses were done for three different conditions.

1. Both of Heat and Moisture Transport Calculation, Use Temperature and Moisture Dependency for Thermal Conductivity, Including All Hygrothermal Special Options
2. Both of Heat and Moisture Transport Calculation, Use Temperature and Moisture Dependency for Thermal Conductivity, Excluding All Hygrothermal Special Options
3. Both of Heat and Moisture Transport Calculation, Use Constant Design Values for Thermal Conductivity, Excluding All Hygrothermal Special Options

In this study, condensation and mold risk in the wall, location of condensation within the wall section, drying time estimation of the initial water content in the wall were analyzed. The following graphs obtained using the results of the simulation were utilized in the analysis. These are:

- Courses

1. Relative Humidity at Monitor Positions – Time
2. Total Water Content in the Wall – Time
3. Water Content in Individual Materials within the Wall Sections – Time

- Profiles

1. Temperature – Wall Section (Distance)
2. Relative Humidity – Wall Section (Distance)
3. Water Content – Wall Section (Distance)

These graphs were created for all wall types. The wall types consisted 3 different body elements (brick, concrete and aerated concrete), 3 different insulation material (XPS, EPS and MW), and in 3 different insulation situations (inner-insulation, outer-insulation and without insulation). In this section, the same wall types in the previous method were selected to show the analysis process due to compare the results. These wall types are:

- Brick wall with internal, external and without XPS insulation
- Aerated Concrete wall with internal, external, without MW insulation
- Concrete wall with internal, external and without EPS insulation

The analyses were done for other wall types. The results of other wall types are given in Appendix from P to V.

Three topics were analyzed with this simulation program. They are whether or condensation risk at the wall, which layer is at condensation risk and drying time estimation of the initial water content in the wall.

- The graph of the total water content-time was utilized to determined condensation risk.
- The graph of relative humidity – time and water content in individual material-time were utilized to determine which layer is at condensation risk.
- The graph was consisted the relative humidity at the monitor positions within the wall and time for two conditions that including all hygrothermal special options and excluding all hygrothermal special options.

4.4.2.4.1. Analyzing Condensation Risk and Condensation Location

Firstly, the graph of total water amount and time was created. The graph of total water content in the wall and time shows whether or condensation risk on the wall. The graph includes the change in amount of the total water in the wall for internal and external insulation in three conditions mentioned on the previous page and time. Also, result of the wall without insulation type was shown in this graph. The total water content is calculated as amount of water in kg per 1 square meter of the wall. The time change is regarded as an hour. The analyses were done for five years. So, x-axis consists of 43800 hours. If the change total water content is sinusoidal and the total water does not increase at the end of a year, there is no condensation risk at this wall.

Secondly, the graph of the relative humidity at monitor positions and time was created. The graph of relative humidity at the monitor positions and time indicates which layer is at risk of condensation. The graph includes the relative humidity at the monitor positions in the wall for internal and external insulation in three conditions mentioned on the previous page and time. Also, the result of the wall without the insulation type was shown in this graph. The relative humidity changes between 0-100%. The time change was regarded as an hour. The analyses were done for five years. So, the x-axis consists of 43800 hours. If the relative humidity is higher than 80% at any layer, condensation risk occurs at this layer. If the relative humidity is higher than 95% at any layer, there is a condensation at this layer.

Lastly, the graph of water amount and time was created. The graph of total water content in the individual materials within the wall and time shows whether or which layer is at risk of condensation. The graph includes the change in the amount of the total water in the wall for internal and external insulation in three conditions mentioned on the previous page and time. Also, the result of the wall without the insulation type was shown in this graph. The water content in the individual materials was calculated as the amount of water in kg per 1 cubic meter of the wall. The time change was regarded as an hour. The analyses were done for five years. So, the x-axis consists of 43800 hours. If the change the water content in the individual material is sinusoidal and the water content does not increase at the end of a year, there is no condensation risk at this wall.

The profiles show temperature, relative humidity and water content distribution in the wall at starting and ending at the simulation period. So, the changes these parameters over the time were analyzed with these profiles. The condensation and location can be determined with this analysis.

- Brick+ XPS

Firstly, the graph of change in total water content in the wall in time was created.

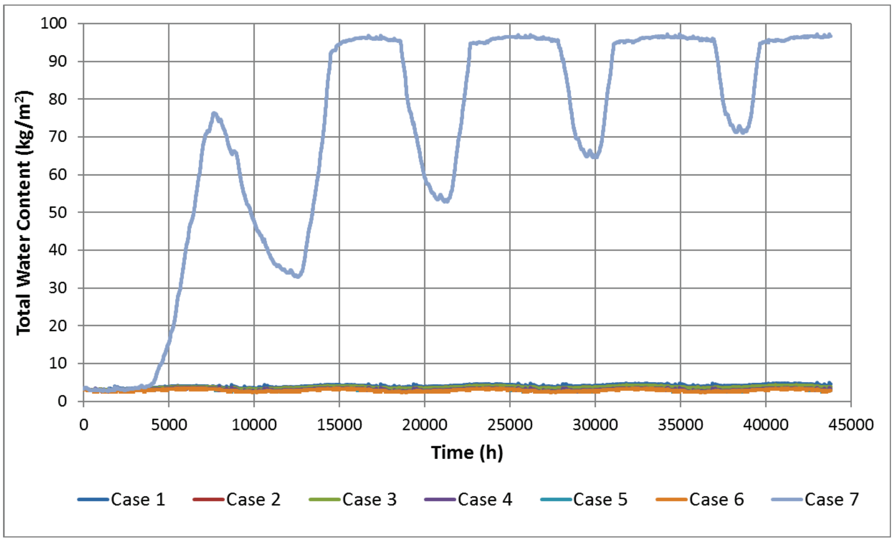


Figure 41. Total Water Content in Brick Wall Types

- Case 1: Wall with internal insulation, Including all hygrothermal parameters, Temperature and moisture dependency for thermal conductivity condition
- Case 2: Wall with internal insulation, Excluding all hygrothermal parameters, Temperature and moisture dependency for thermal conductivity condition
- Case 3: Wall with internal insulation, Excluding all hygrothermal parameters, Constant Design Values for Thermal Conductivity
- Case 4: Wall with external insulation, Including all hygrothermal parameters, Temperature and moisture dependency for thermal conductivity condition
- Case 5: Wall with external insulation, Excluding all hygrothermal parameters, Temperature and moisture dependency for thermal conductivity condition
- Case 6: Wall with external insulation, Excluding all hygrothermal parameters, Constant Design Values for Thermal Conductivity
- Case 7: Wall without insulation, Including all hygrothermal parameters, Temperature and moisture dependency for thermal conductivity condition

The above-mentioned explanations of the cases are valid for the same graphs created for other wall types.

The first year of the simulation period is not considered in the result analysis process due to the time of equilibrium. Although the condensed water vapor evaporated in spring and summer, the condensed water vapor did not evaporate wholly at the end of the year. The most total water amount change occurred in brick wall without insulation (Case 7) as 31 kg/m^2 according to Figure 41. This situation can cause mold growth.

Figure 42 does not include Case 7 due to analyze the other cases in detail. Total water content decreased according to the initial state in the brick walls with external insulation cases which are Case 4, 5 and 6 at the end of 5 years. The total amount of water changed sinusoidal. The water vapor condensed in winter and evaporated in summer totally. So, these walls types are suitable in terms of interstitial condensation. The pick points show the rainy hours.

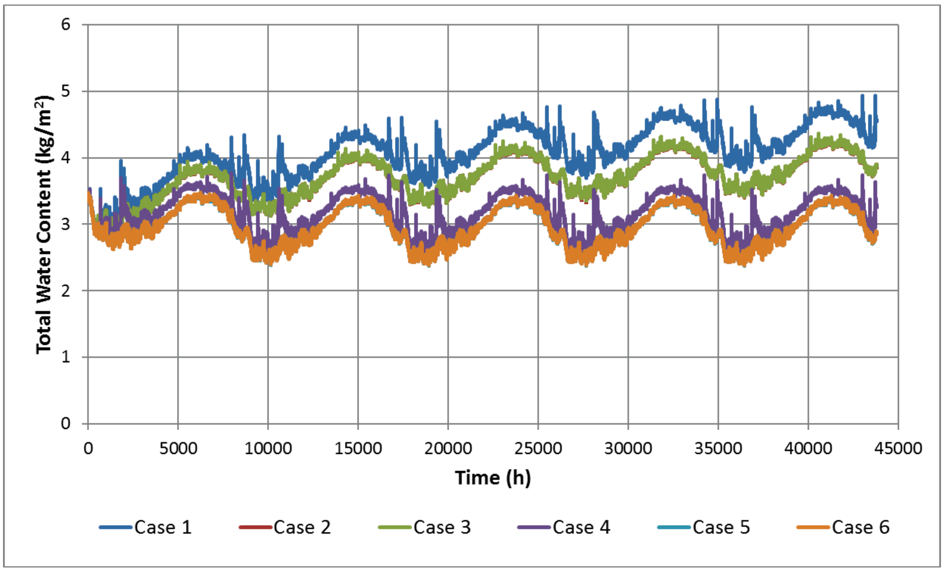


Figure 42. Total Water Content in Brick Wall Types (except Case 7)

Total water content increased according to the initial state in the brick walls with internal insulation cases which are Case 1,2 and 3 at the end of the simulation period. The first year of the simulation period is not considered in the result analysis process due to the time of equilibrium. The total amount of water changed sinusoidally. Although the condensed water vapor evaporated in spring and summer, the condensed water vapor did not evaporate wholly at the end of the year. The total water amount change of Case 1, Case 2 and Case 3 are 0.591, 0.365 and 0.367 kg/m^2, respectively. The most water content change is in Case 1. So, Case 1 is at most condensation risk. This situation can cause moisture problems and mold growth.

The graphs of the relative humidity at the monitor positions-time and the water content amount in individual material-time were created for Case 1 that is brick wall with internal XPS with including all hygrothermal parameters and temperature and moisture dependency for thermal conductivity condition. The pick points show the rainy hours.

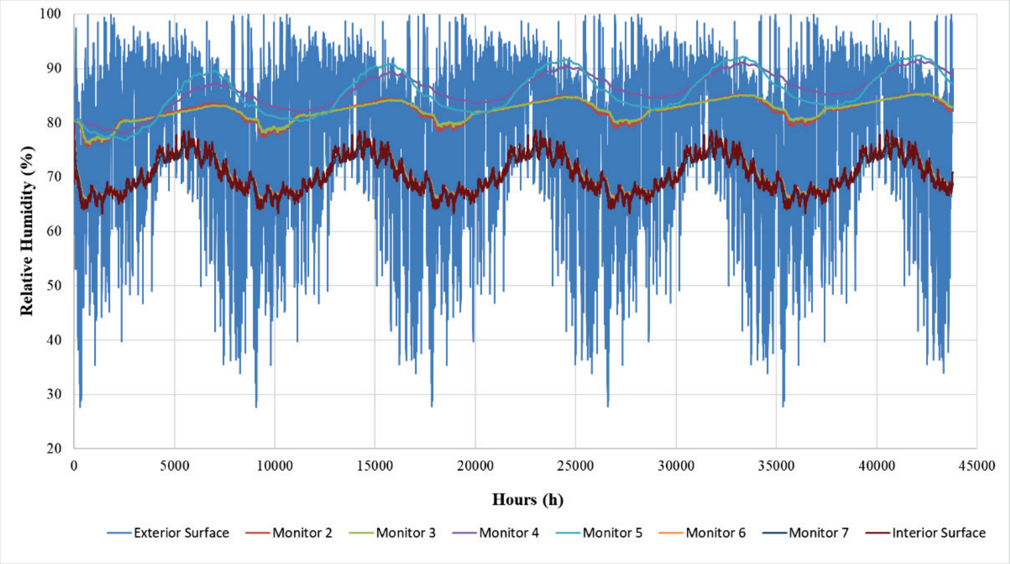


Figure 43. Relative Humidity at Monitor Positions in Brick with Internal XPS

The monitor positions are described as follows;

- Monitor 2; Warm Side of Cement Plaster,
- Monitor 3; Cold Side of Brick, Monitor 4; Warm Side of Brick,
- Monitor 5; Cold Side of XPS, Monitor 6: Warm Side of XPS,
- Monitor 7; Cold Side of Lime Plaster

Since the system had reached equilibrium at the end of one year, the first year is not included in the analysis. Monitor 2,3,4 and 5 are at condensation risk in winter according to Figure 43 due to the relative humidity is higher than 80%. The most condensation risk is at interlayer between brick and XPS.

The graph of water content in individual material and time was created for determining whether or condensation. Also, this graph shows the location of condensation. Figure 44 represents the water amount in the individual material.

There is condensation at layers of cement plaster, brick, XPS and lime plaster according to Figure 44 and Table 18. The change in water content of the wall is 590 gr/m^2 at the end of 5 years as shown in Figure 41. There is no risk of freezing by the reason of the condensation due to the relative humidity is lower than 95% and the temperature is higher than 0^{o}C according to result of WUFI Bio. So, locating the XPS insulation in outer of the wall is more useful than inner side of the wall. The condensed water amounts in layers are shown in Table 17. The water content in individual materials is calculated as the amount of water in kg per 1 cubic meter of the wall.

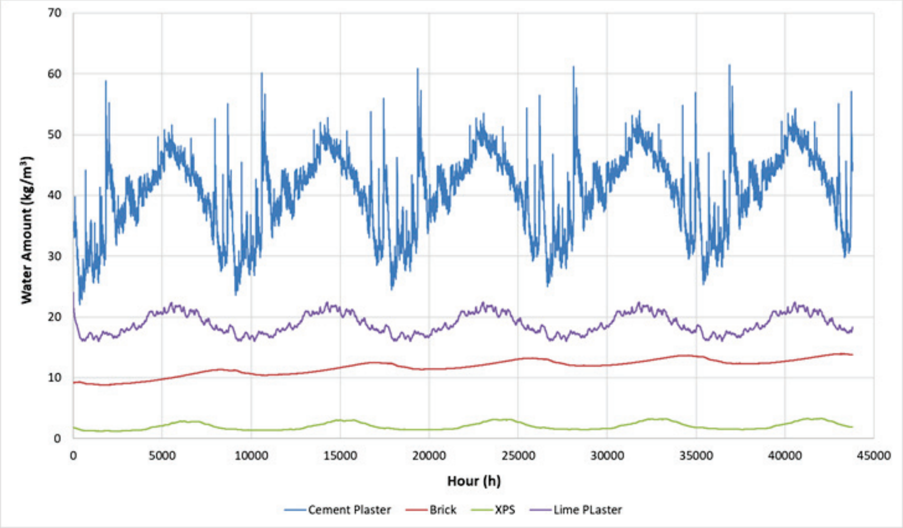


Figure 44. Water Content in Layers within Brick Wall with Internal XPS

Table 17. Water Content in Layers within Brick Wall with Inner XPS insulation

	Water Content (kg/m^3)				
	Start	**End**	**Max**	**Min**	**Δm**
Cement Plaster	42.36	44.43	61.46	23.62	2.07
Brick	11.20	13.75	13.93	10.40	2.55
XPS	1.55	1.86	3.30	1.35	0.31
Lime Plaster	18.33	18.38	22.44	15.99	0.05

The temperature, relative humidity and water content distributions in the wall were shown in the above profile graphs. Also, Figures show the effects of the presence and location of insulation. The distance axis of the graph starts at the outer side of the wall and finishes at the inner side of the wall.

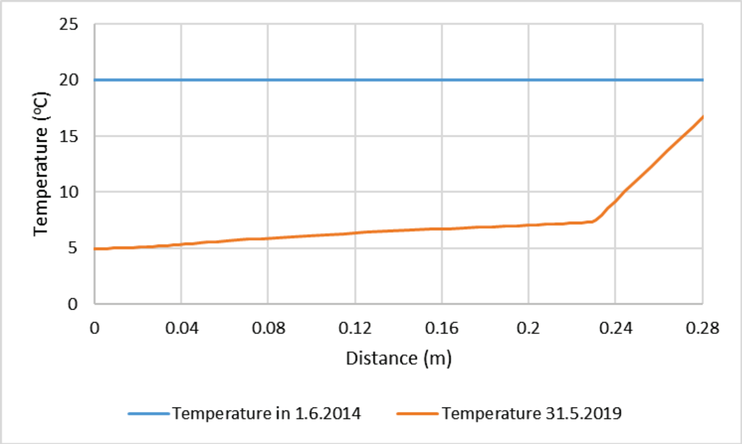


Figure 45. Temperature Distributions in Brick Wall with Internal XPS Insulation

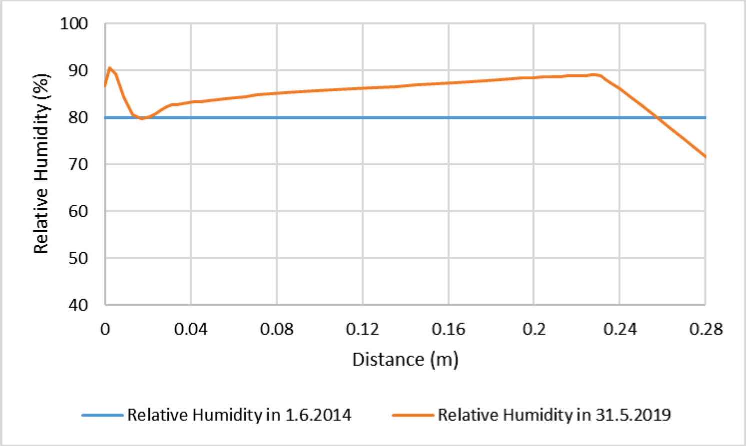


Figure 46. Relative Humidity Distributions in Brick Wall with Internal XPS Insulation

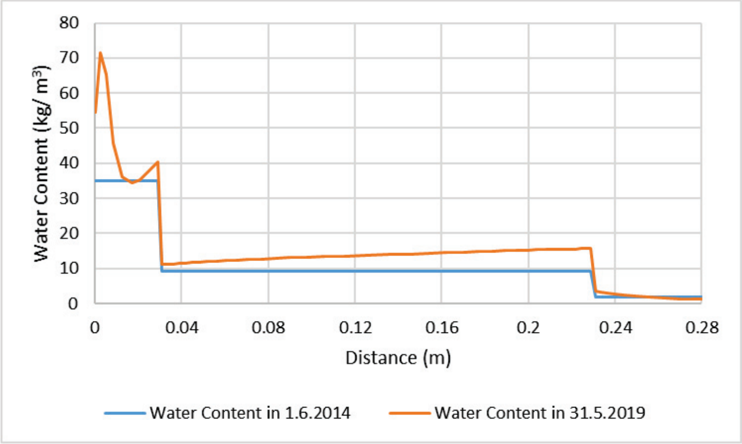


Figure 47. Water Content Distributions in Brick Wall with Internal XPS Insulation

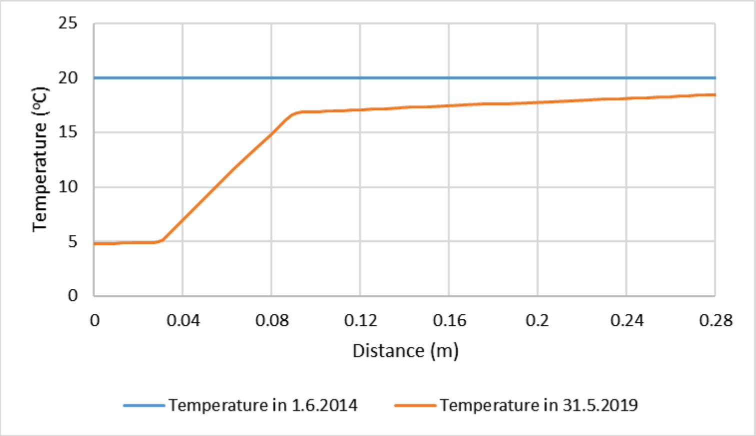


Figure 48. Temperature Distributions in Brick Wall with External XPS Insulation

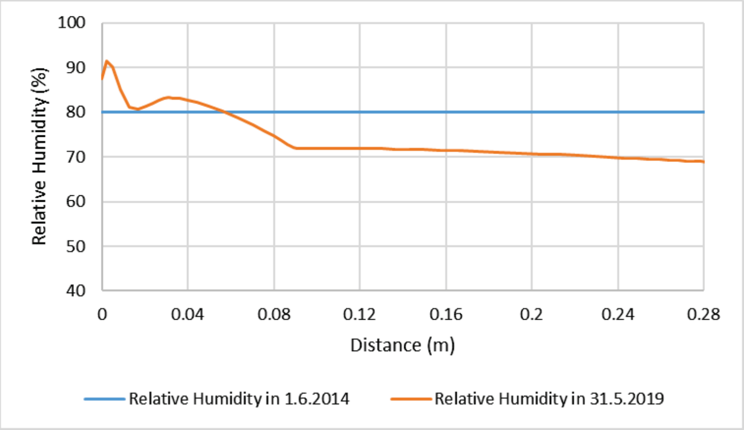


Figure 49. Relative Humidity Distributions in Brick Wall with External XPS Insulation

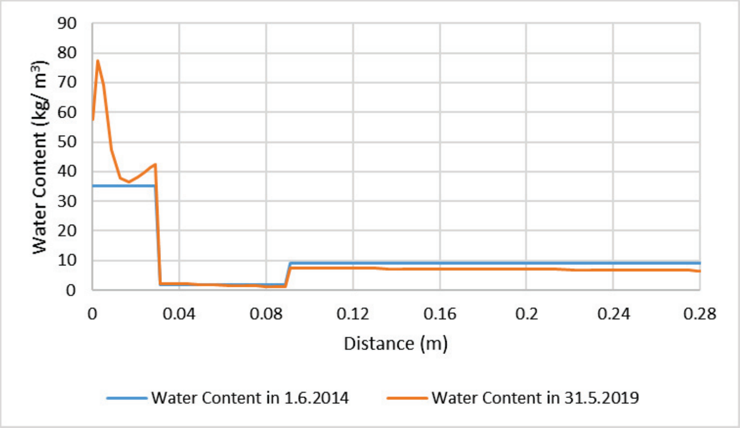


Figure 50. Water Content Distributions in Brick Wall with External XPS Insulation

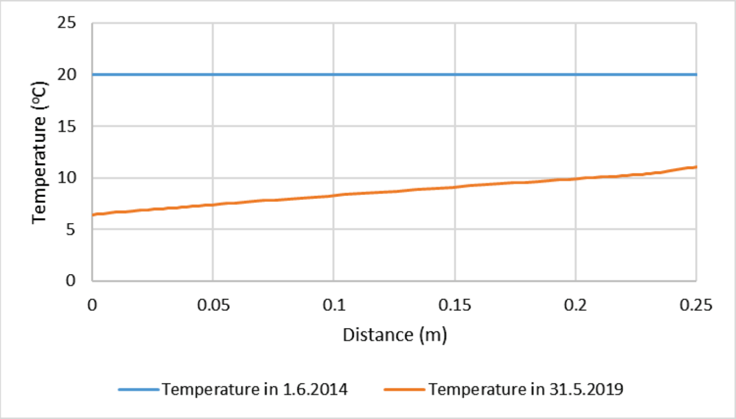


Figure 51. Temperature Distributions in Brick Wall without Insulation

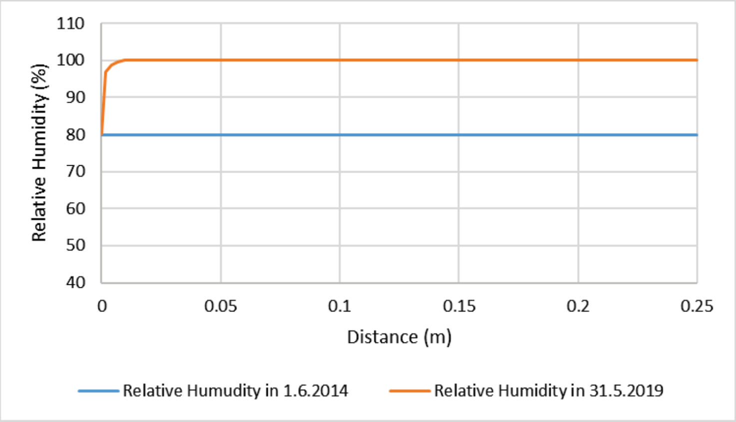


Figure 52. Relative Humidity Distributions in Brick Wall without Insulation

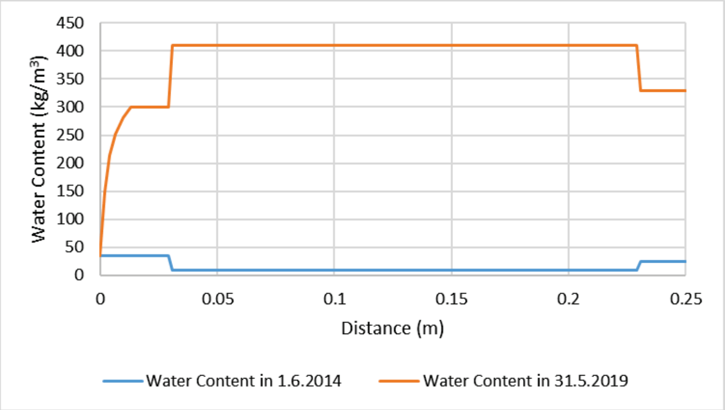


Figure 53. Water Content Distributions in Brick Wall without Insulation

When the examining the figures, the following inferences were obtained. There are;

- The insulation material is a key point for heat and moisture transfer in the wall. When using internal insulation, the temperature is low throughout up to insulation material. If the insulation material is not used, temperature increases from outside to inside in low value that is closer to the outside temperature. When using external insulation, temperature throughout the wall is close to the ambient temperature.
- When using internal insulation, the relative humidity is higher value throughout wall than beginning value up to insulation material. The relative humidity increases up to 90% If the insulation material is not used, relative humidity is 100% throughout wall When using external insulation, relative humidity is lower than the beginning value throughout the wall. The relative humidity is generally 70% throughout the wall.
- When using internal insulation, the water content is higher value throughout the wall than the beginning value up to lime plaster. If the insulation material is not used water content is very high throughout the wall. The water content increases up to 400 kg/m^3. When using external insulation, relative water content is lower than the beginning value throughout the wall.

When these inferences are taken into consideration, the temperature and relative humidity, which are important factors for heat and moisture transfer in the building wall, are closely related to each other and inversely proportional. Relative humidity should be kept lower than the critical value since the increase in relative humidity causes condensation. The location of insulation material is very important owing to affect the temperature distribution within the wall.

The results of brick wall types with EPS and MW are given Appendix P and R, respectively. Concrete wall types with EPS and aerated concrete wall types with MW were analyzed due to compare the results of previous calculation and WUFI Pro simulation model.

- Concrete + EPS

Firstly, graph consisted total water content in the wall and time was created. There are results of seven cases in Figure 54. The explanations of cases are given Page 66. The same graph re-created by excluding case 7.

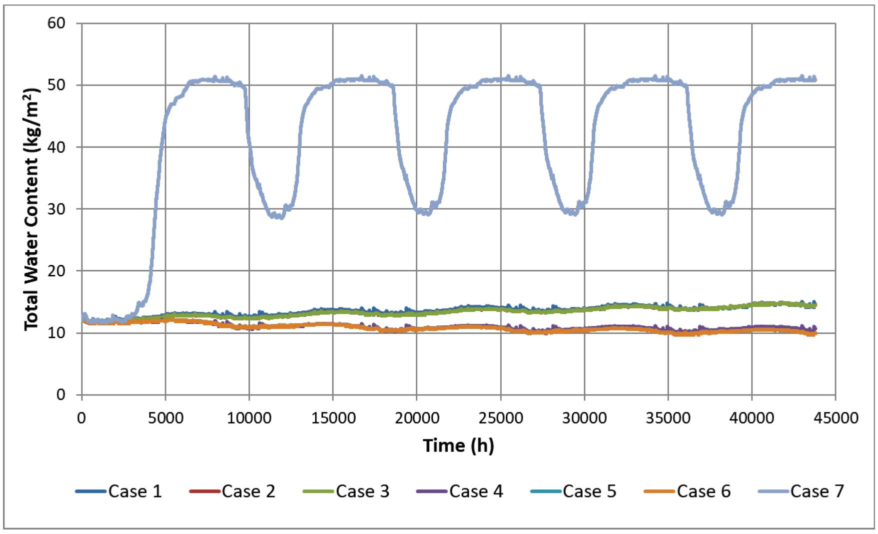


Figure 54. Total Water Content in Concrete Wall Types

The first year of the simulation period is not considered in the result analysis process due to the time of equilibrium. After 5 year, the most total water content is in the concrete wall without insulation but almost all condensed water vapor evaporated at the end of a year. The amount of condensed water vapor is 0.080 kg/m^2 at the end of simulation period in the concrete wall without insulation. The total water amount of concrete wall with internal EPS increased during the simulation process according to Figure 54. This situation can cause mold growth. Figure 55 does not include Case 7 due to analyze the other cases in detail.

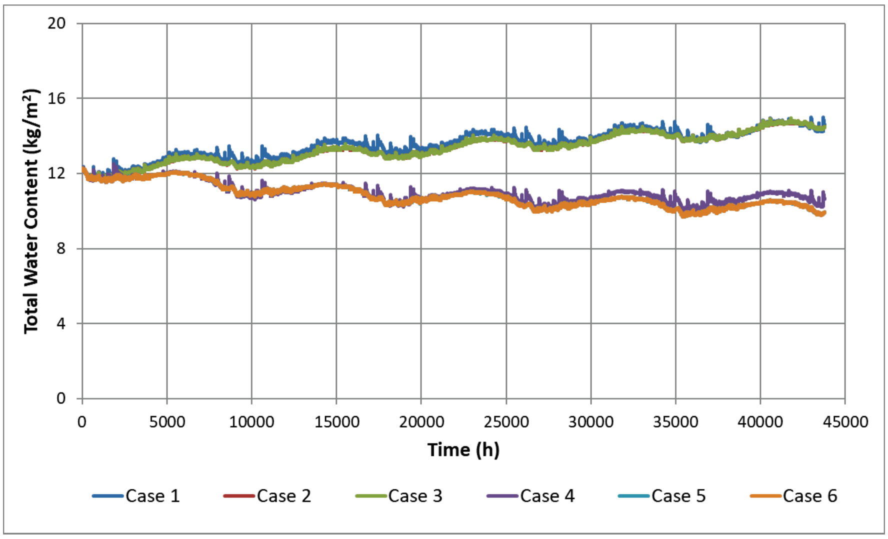


Figure 55. Total Water Content in Concrete Wall Types (except Case 7)

Total water content decreased according to the initial state in the concrete walls with external insulation cases which are Case 4,5 and 6 at the end of simulation period. The total amount of water changed sinusoidally. The water vapor condensed in winter and evaporated in summer totally. So, these walls types are suitable in terms of interstitial condensation. The pick points show the rainy hours.

Total water content increased according to the initial state in the concrete walls with internal insulation cases which are Case 1,2 and 3 at the end of the simulation period. The first year of the simulation period is not considered in the result analysis process due to the time of equilibrium. The total amount of water changed sinusoidally. Although the condensed water vapor evaporated in spring and summer, the condensed water vapor did not evaporate wholly at the end of the year. The total water amount change of Case 1, Case 2 and Case 3 are 1.55, 1.88 and 1.88 kg/m^2, respectively. So, these cases are at condensation risk. This situation can cause moisture problems and mold growth.

The graphs of the relative humidity at the monitor positions-time and the water content amount in individual material-time were created for Case 1 that is concrete wall with internal EPS with including all hygrothermal parameters and temperature and moisture dependency for thermal conductivity condition. The pick points show the rainy hours.

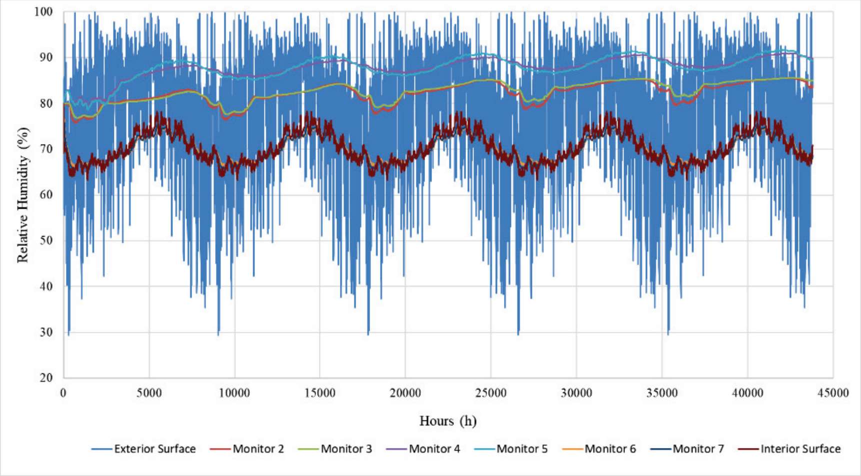


Figure 56. Relative Humidity at the Monitor Positions in Concrete with Inner EPS

The monitor positions are described as follows;

- Monitor 2; Warm Side of Cement Plaster,

- Monitor 3; Cold Side of Concrete, Monitor 4; Warm Side of Concrete,
- Monitor 5; Cold Side of EPS, Monitor 6: Warm Side of EPS,
- Monitor 7; Cold Side of Lime Plaster

Since the system had reached equilibrium at the end of one year, the first year is not included in the analysis. Monitor 2,3,4 and 5 are at condensation risk in winter according to Figure 57 due to the relative humidity is higher than 90% at the end of the simulation time. The most condensation risk is at interlayer between concrete and EPS.

The graph of water content in individual material and time was created for determining whether or condensation. Also, this graph shows the location of condensation. Figure 57 represents the water amount in the individual material.

There is condensation at layers of cement plaster, concrete, EPS and lime plaster according to Figure 57 and Table 19. The change in water content of the wall is 1550 gr/m^2 at the end of the simulation time as shown in Figure 54 There is no risk of freezing by the reason of the condensation due to the relative humidity is lower than 95% and the temperature is higher than 0^{o}C according to result of WUFI Bio. So, locating the EPS insulation in outer of the wall is more useful than inner side of the wall. The condensed water amounts in layers are shown in Table 18. The condensation is affective in cement plaster and concrete materials according to this table. The water content in individual materials is calculated as the amount of water in kg per 1 cubic meter of the wall.

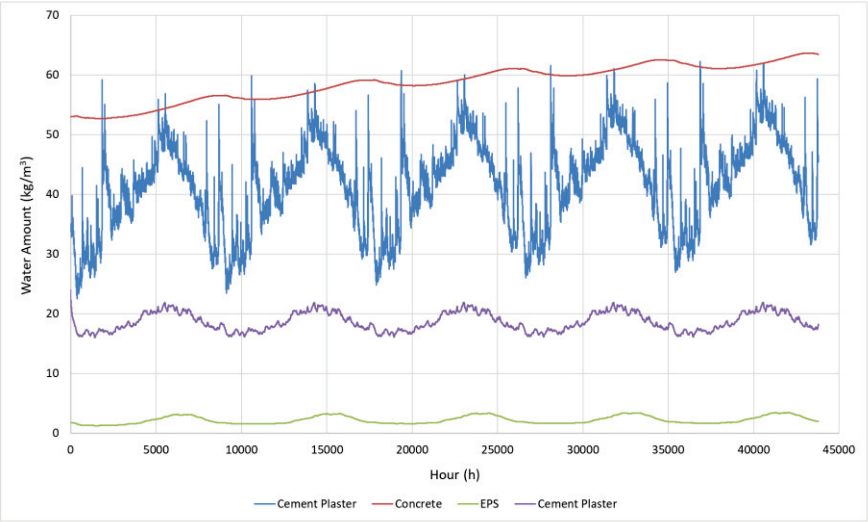


Figure 57. Water Content in Layers within the Concrete Wall with Inner EPS

Table 18. Water Content in Layers within Concrete Wall with Internal EPS

	Water Content (kg/m^3)				
	Start	**End**	**Max**	**Min**	**Δm**
Cement Plaster	41.38	45.70	62.26	23.48	4.32
Concrete	56.52	63.50	63.66	55.90	6.98
EPS	1.75	1.99	3.47	1.54	0.24
Lime Plaster	18.23	18.27	21.92	16.09	0.04

The temperature, relative humidity and water content distributions in the wall were shown in the below profile graphs. Also, Figures show the effects of the presence and location of insulation. The distance axis of the graph starts at the outer side of the wall and finishes at the inner side of the wall.

When the examining the figures, the following inferences were obtained. There are;

- The insulation material is a key point for heat and moisture transfer in the wall. When using internal insulation, the temperature is closer to the outside temperature throughout the wall up to insulation material. If the insulation material is not used, the temperature is low throughout the wall. The temperature of the wall is closer to the outside temperature. When using external insulation, temperature throughout the wall is close to the ambient temperature. The wall temperature approaches the internal temperature value after the insulation part.
- When using internal insulation, the relative humidity is higher value throughout wall than beginning value up to insulation material. The relative humidity increases up to 90% If the insulation material is not used, relative humidity is 100% throughout wall When using external insulation, relative humidity is lower than the beginning value throughout the wall. The relative humidity is generally 60% throughout the wall.
- When using internal insulation, the water content is higher value throughout the wall than the beginning value up to lime plaster. If the insulation material is not used water content is very high throughout the wall. The water content increases up to 200 kg/m^3. When using external insulation, relative water content is lower than the beginning value throughout the wall.

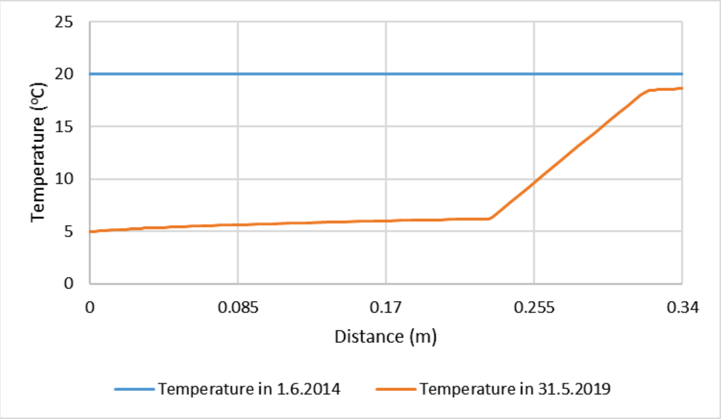


Figure 58. Temperature Distribution in Concrete Wall with Internal EPS Insulation

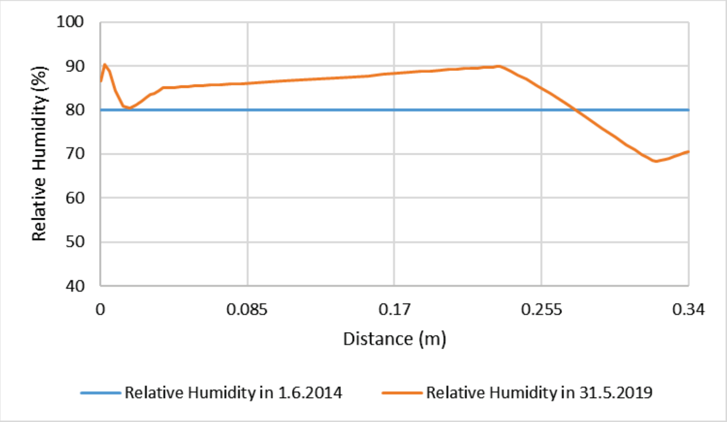


Figure 59. Relative Humidity Distribution in Concrete Wall with Internal EPS Insulation

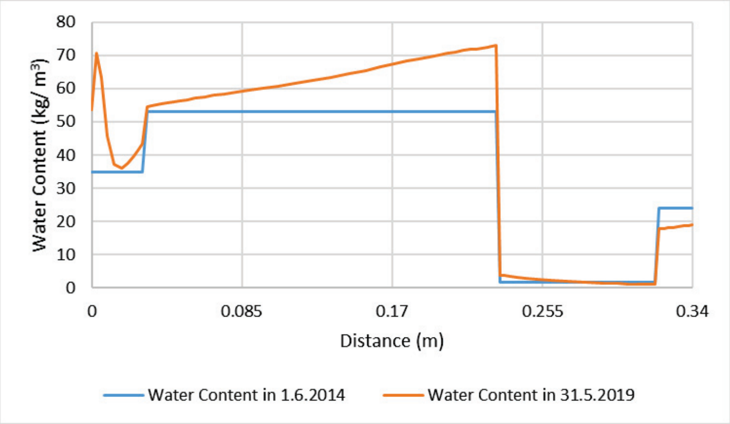


Figure 60. Water Content Distribution in Concrete Wall with Internal EPS Insulation

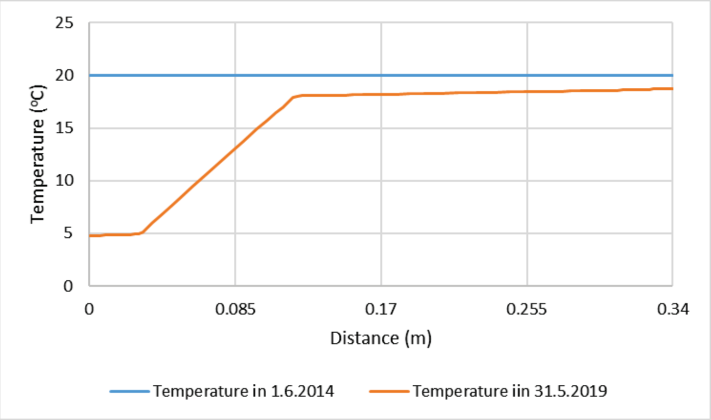


Figure 61. Temperature Distribution in Concrete Wall with External EPS Insulation

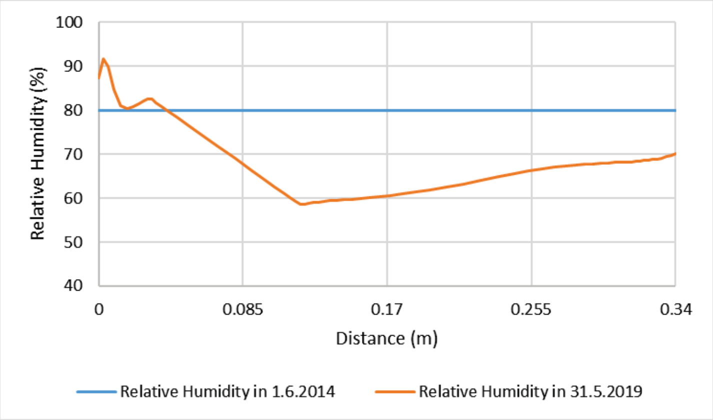


Figure 62. Relative Humidity Distribution in Concrete Wall with External EPS Insulation

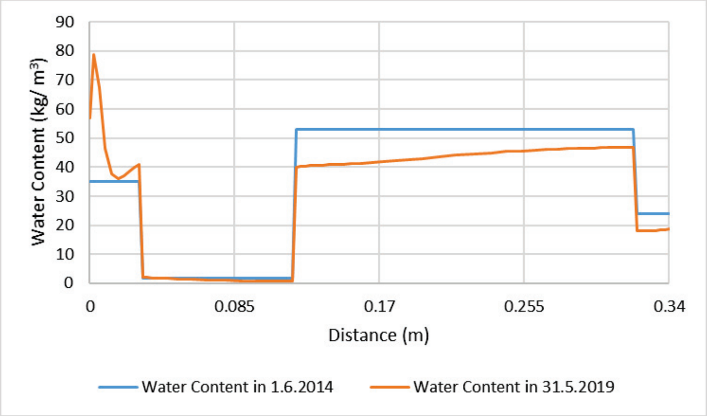


Figure 63. Water Content Distribution in Concrete Wall with External EPS Insulation

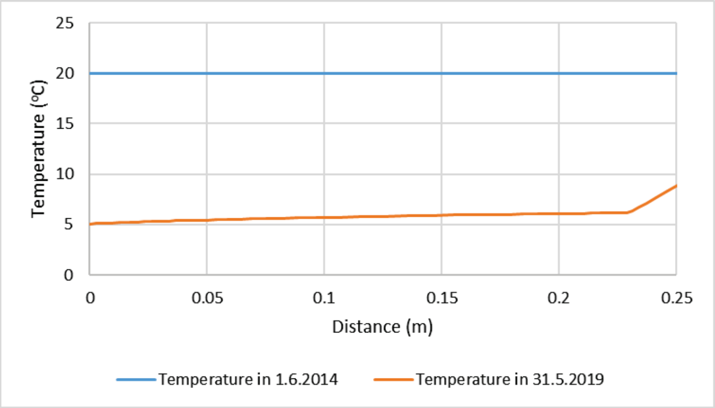


Figure 64. Temperature Distribution in Concrete Wall without Insulation

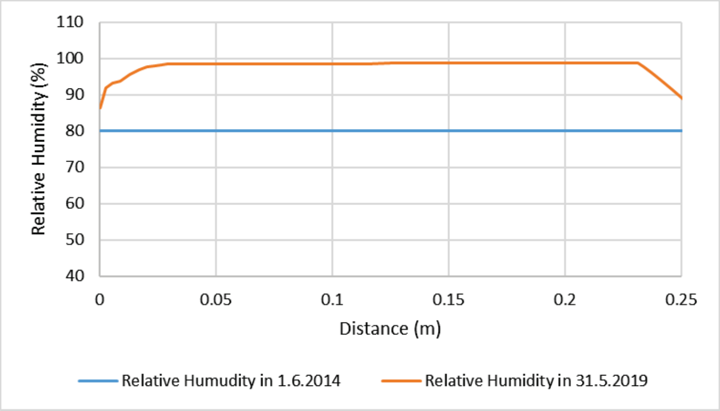


Figure 65. Relative Humidity Distribution in Concrete Wall without Insulation

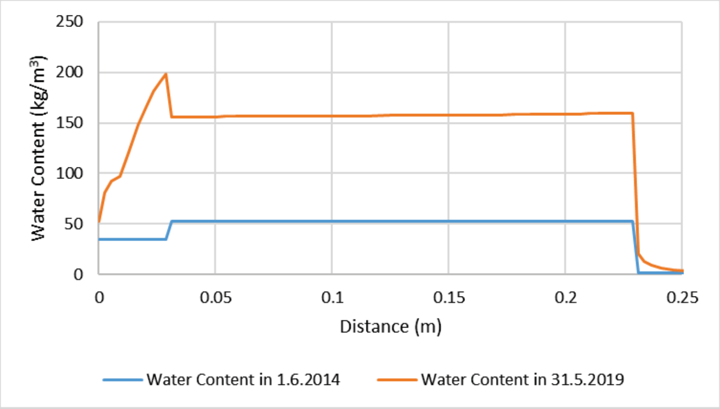


Figure 66. Water Content Distribution in Concrete Wall without Insulation

When these inferences are taken into consideration, the similar results were obtained between brick wall with XPS insulation. The insulation material and its location are very significant for hygrothermal analysis. The results of concrete wall types that are with XPS and MW are given Appendix S and T.

- Aerated Concrete + MW

Firstly, graph consisted total water content in the wall and time was created. There are results of seven cases in Figure 67. The explanations of cases are given Page 66.

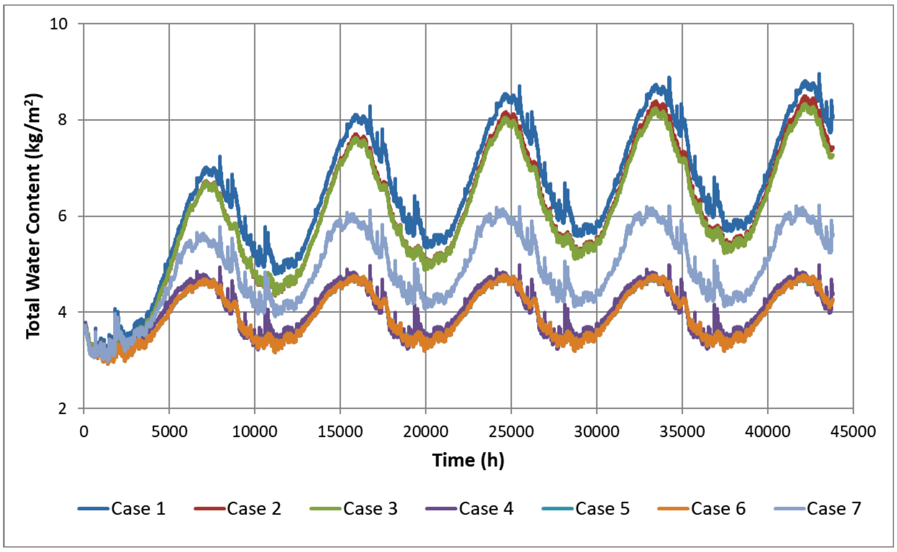


Figure 67. Total Water Content in Aerated Concrete Wall Types with MW

The first year of the simulation period is not considered in the result analysis process due to the time of equilibrium. After 1 year, the total water contents of wall types start changing by sinusoidal. According to Figure 67, the total water content of all aerated concrete wall types with MW increases but the aerated concrete wall types with external MW and without insulation show little changes. The most total water content changes in Case 1, 2 and 3. So, these cases are at most condensation risk. The most total water content is in Case 1 that is aerated concrete wall with internal MW in including all hygrothermal parameters, temperature and moisture dependency for thermal conductivity condition. The pick points show the rainy hours.

The graphs of the relative humidity at the monitor positions-time and the water content amount in individual material-time were created for Case 1 that is aerated concrete wall with internal MW with including all hygrothermal parameters and temperature and moisture dependency for thermal conductivity condition. The pick points show the rainy hours.

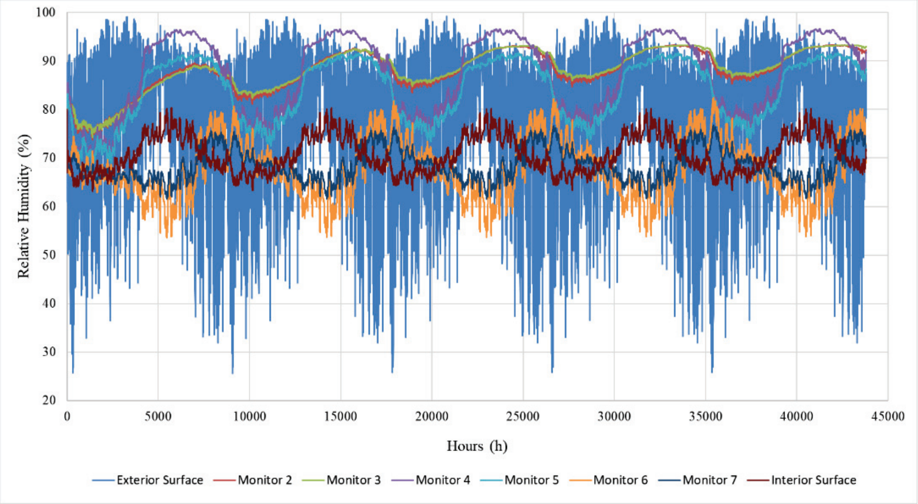


Figure 68. Relative Humidity at Monitor Positions in Aerated Concrete Wall with Internal MW

The monitor positions are described as follows;

- Monitor 2; Warm Side of Cement Plaster,
- Monitor 3; Cold Side of Aerated Concrete, Monitor 4; Warm Side of Aerated Concrete,
- Monitor 5; Cold Side of MW, Monitor 6: Warm Side of MW,
- Monitor 7; Cold Side of Lime Plaster

Since the system had reached equilibrium at the end of one year, the first year is not included in the analysis. Monitor 2,3,4 and 5 are at condensation risk in winter according to Figure 68 due to the relative humidity is higher than 90-95% at the end of the simulation time. The most condensation risk is at interlayers between cement plaster and aerated concrete, aerated concrete and MW. The condensation takes place most probably in Monitor 4. This situation causes mold growth and moisture problems within the wall.

The graph of water content in individual material and time was created for determining whether or condensation. Also, this graph shows the location of condensation. Figure 69 represents the water amount in the individual material.

There is condensation at layers of cement plaster, aerated concrete, MW and lime plaster according to Figure 69 and Table 19. The change in water content of the wall is 1530 gr/m^2 at the end of the simulation time as shown in Figure 67 There is a risk of freezing by the reason of the condensation due to the relative humidity is higher than 95%. So, locating the MW insulation in outer of the wall is more useful than inner side of the wall. The condensed water amounts in layers are shown in Table 20. The water content in individual materials is calculated as the amount of water in kg per 1 cubic meter of the wall. The condensation occurs in between cement plaster and aerated concrete. The water content changes of these materials are 9.08 and 5.84 kg/m^3, respectively.

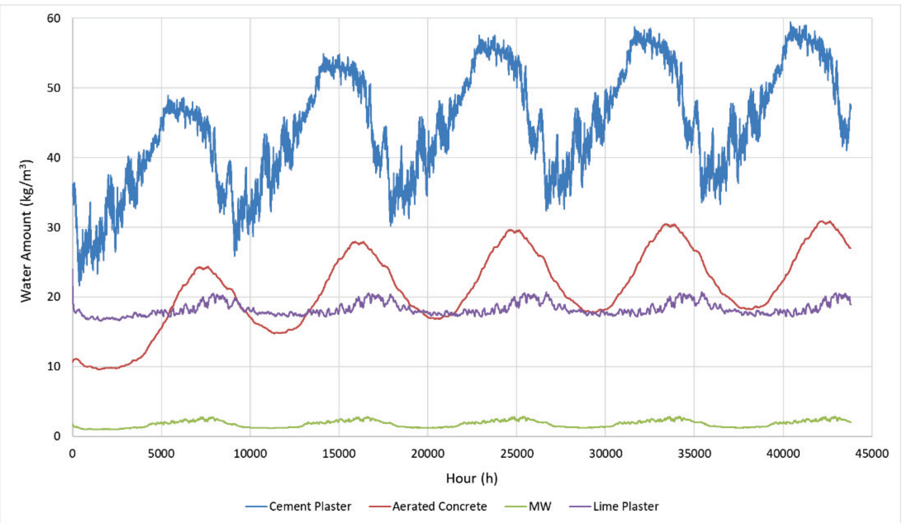


Figure 69. Water Content in Layers within Aerated Concrete Wall with Internal MW

Table 19. Water Content in Layers within Aerated Concrete with Internal MW

	Water Content (kg/m^3)				
	Start	**End**	**Max**	**Min**	**Δm**
Cement Plaster	38.50	47.59	59.44	25.90	9.08
Aerated Concrete	21.21	27.05	30.90	14.76	5.84
MW	1.75	2.02	2.84	1.17	0.27
Lime Plaster	18.49	18.90	20.76	17.14	0.42

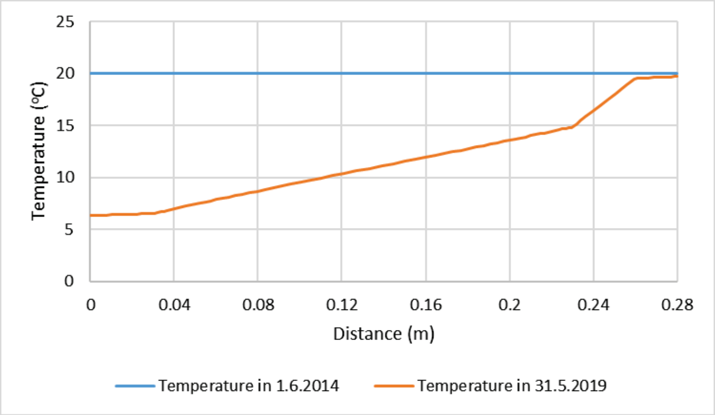


Figure 70. Temperature Distributions in Aerated Concrete Wall with Internal MW Insulation

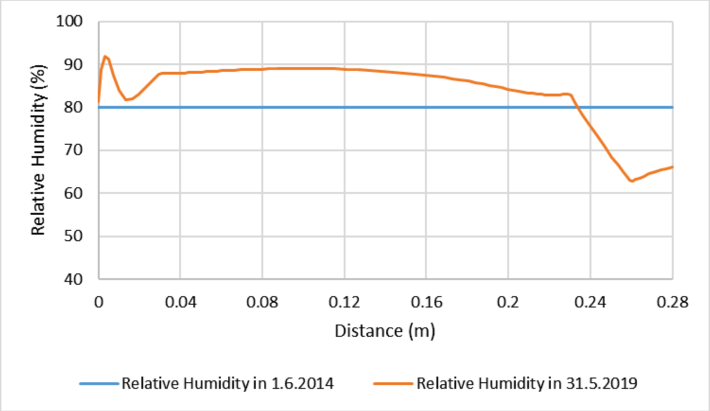


Figure 71. Relative Humidity Distributions in Aerated Concrete Wall with Internal MW Insulation

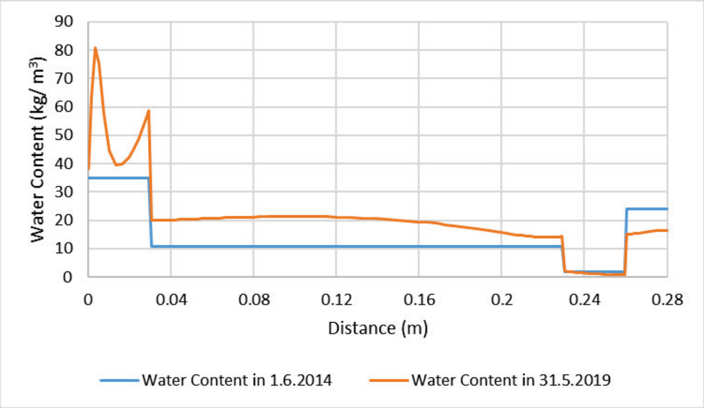


Figure 72. Water Content Distributions in Aerated Concrete Wall with Internal MW Insulation

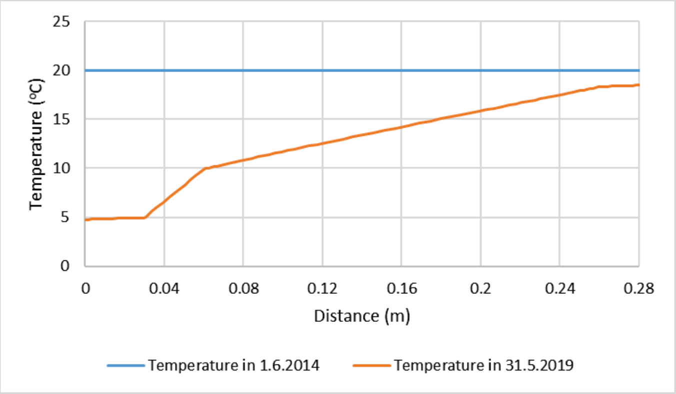


Figure 73. Temperature Distributions in Aerated Concrete Wall with External MW Insulation

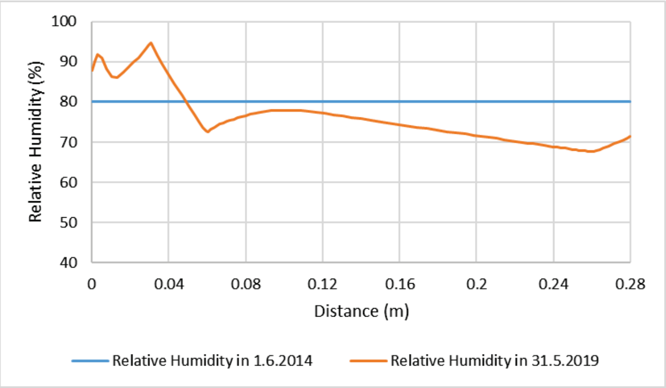


Figure 74. Relative Humidity Distributions in Aerated Concrete Wall with External MW Insulation

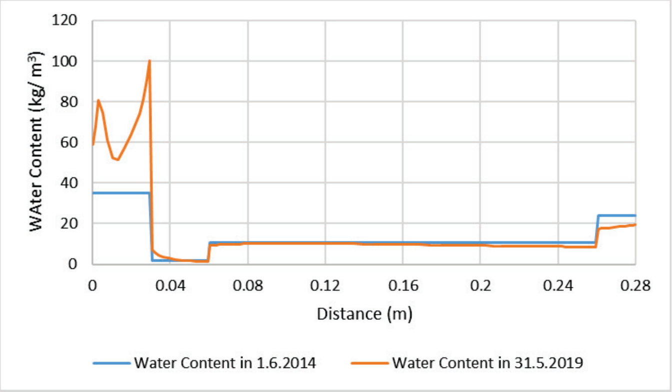


Figure 75. Water Content Distributions in Aerated Concrete Wall with External MW Insulation

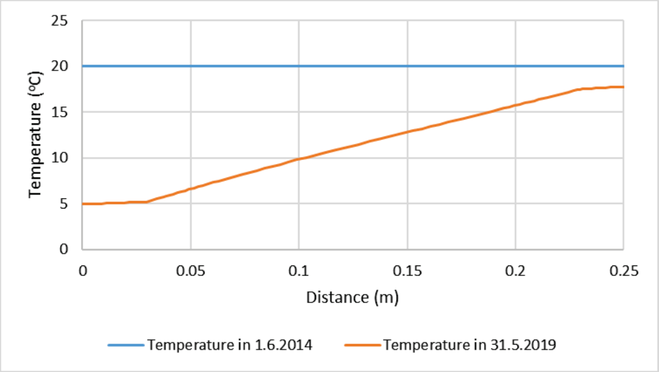


Figure 76. Temperature Distributions in Aerated Concrete Wall without Insulation

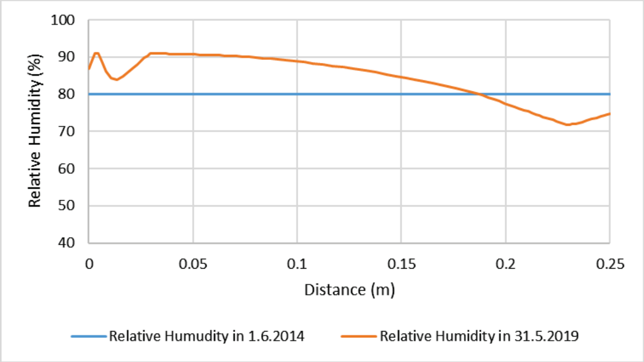


Figure 77. Relative Humidity Distributions in Aerated Concrete Wall without Insulation

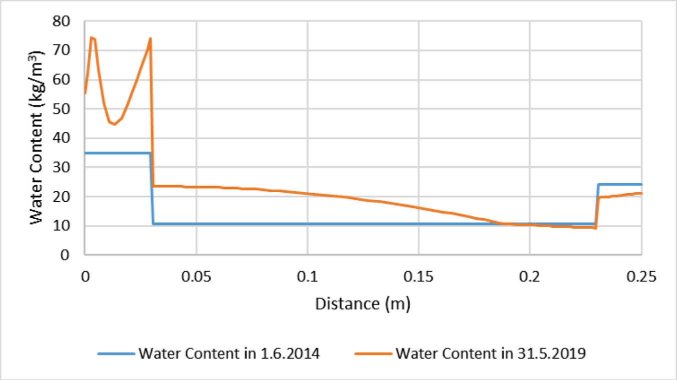


Figure 78. Water Content Distributions in Aerated Concrete Wall without Insulation

When the examining the figures, the following inferences were obtained. There are;

- When using internal insulation, the temperature is low throughout up to insulation material. If the insulation material is not used, temperature increases from outside to inside in low value that is closer to the outside temperature. When using external insulation, temperature throughout the wall is close to the ambient temperature. The wall with external insulation gives the better results than other wall types. The temperature distribution of aerated concrete wall external insulation is similar to aerated concrete wall without insulation.
- When using internal insulation, the relative humidity is higher value throughout wall than beginning value up to insulation material. The relative humidity is close by 90% throughout the wall. If the insulation material is not used, relative humidity is 90% throughout wall. The aerated concrete without insulation gives the better results than aerated concrete wall with internal MW. When using external insulation, relative humidity is lower than the beginning value throughout the wall. The relative humidity is generally 70% throughout the wall.
- When using internal insulation, the water content is higher value throughout the wall than the beginning value up to lime plaster. If the insulation material is not used water content is very high throughout the wall. The water content increases up to 400 kg/m^3. When using external insulation, relative water content is lower than the beginning value throughout the wall.

When these inferences are taken into consideration, the temperature and relative humidity, which are important factors for heat and moisture transfer in the building wall, are closely related to each other and inversely proportional. Relative humidity should be kept lower than the critical value since the increase in relative humidity causes condensation. The location of insulation material is very important owing to affect the temperature distribution within the wall.

The condensation occurred in cement plaster and aerated concrete. The water content in these individual materials increases in both internal insulation and without insulation cases. The results of concrete wall types that are with XPS and MW are given Appendix S and .T.

Consequently, the total water amounts in the brick wall, concrete wall and aerated concrete wall types were shown in Table 20, 21 and 22, respectively. The wall types were analyzed in 3 different situations that are Case 1, Case 2 and Case 3. The cases were explained in Page 67.

- Brick Wall

Table 20. Total Water Contents in Brick Wall Types

Wall Types				**Total Water Content (kg/m^2)**				
				Start	**End**	**Max**	**Min**	**Δm**
Brick	**EPS**	**Internal**	**Case 1**	4.23	5.12	5.51	3.55	0.89
			Case 2	3.78	4.46	4.90	3.34	0.67
			Case 3	3.78	4.45	4.90	3.35	0.67
		External	**Case 1**	3.35	3.32	3.77	2.50	-0.03
			Case 2	2.95	2.92	3.45	2.38	-0.03
			Case 3	2.95	2.92	3.46	2.38	-0.04
	XPS	**Internal**	**Case 1**	3.97	4.56	4.94	3.33	0.59
			Case 2	3.53	3.89	4.35	3.12	0.37
			Case 3	3.53	3.90	4.36	3.12	0.37
		External	**Case 1**	3.32	3.29	3.74	2.50	-0.02
			Case 2	2.91	2.88	3.42	2.38	-0.03
			Case 3	2.92	2.89	3.43	2.38	-0.03
	MW	**Internal**	**Case 1**	11.18	24.66	25.36	8.93	13.47
			Case 2	10.64	27.95	28.29	8.11	17.31
			Case 3	10.42	23.80	24.33	7.88	13.38
		External	**Case 1**	3.59	3.59	4.13	2.61	-0.01
			Case 2	3.41	3.42	3.89	2.57	0.00
			Case 3	3.41	3.41	3.89	2.56	0.00
	Without		**Case 1**	65.79	96.67	97.24	32.86	30.88

There are condensation points in brick wall with internal XPS, EPS and MW insulation according Table 20. The obtained inferences from the Table 20 as follows;

- The most condensed water amount is in brick wall without insulation in Case 1 as 30.88 kg/m^2.
- The lowest condensed water amount is in brick wall with internal XPS in Case 2 and 3 as 0.37 kg/m^2.

- The results of brick wall types with external insulations are the best and same. The water evaporated at the end of 5 years as 30 g/m^2.
- Locating the insulation material on the outer side of the wall is more useful than on inner side of the wall.
- Also, this table showed the effect of liquid transfer and latent heat transfer at the hygrothermal behavior of the wall. The water content in the wall types with inner insulation in Case 2 is lower than in Case 1 except MW. The brick wall with internal MW in Case 2 has more condensed water amount than Case 1.

- Concrete Wall

Table 21. Total Water Contents in Concrete Wall Types

Wall Types				**Total Water Content (kg/m^2)**				
				Start	**End**	**Max**	**Minx**	**Δm**
Concrete	**EPS**	**Internal**	**Case 1**	13.07	14.61	15.01	12.47	1.55
			Case 2	12.63	14.50	14.94	12.27	1.88
			Case 3	12.63	14.51	14.95	12.27	1.88
		External	**Case 1**	11.49	10.66	11.65	9.98	-0.82
			Case 2	11.29	9.95	11.47	9.70	-1.34
			Case 3	11.29	9.96	11.47	9.70	-1.33
	XPS	**Internal**	**Case 1**	12.79	13.81	14.24	12.21	1.02
			Case 2	12.37	13.65	14.16	12.00	1.28
			Case 3	12.37	13.65	14.18	12.01	1.29
		External	**Case 1**	11.54	10.80	11.74	10.14	-0.75
			Case 2	11.34	10.14	11.55	9.88	-1.20
			Case 3	11.34	10.14	11.56	9.89	-1.20
	MW	**Internal**	**Case 1**	20.87	36.14	37.13	18.93	15.27
			Case 2	20.02	43.70	43.85	17.96	23.68
			Case 3	19.67	36.54	36.92	17.53	16.87
		External	**Case 1**	10.72	9.95	10.95	9.26	-0.77
			Case 2	10.90	9.34	11.02	9.06	-1.56
			Case 3	10.90	9.34	11.03	9.06	-1.56
	Without		**Case 1**	50.77	50.85	51.52	28.54	0.08

There are condensation points in concrete wall with internal XPS, EPS and MW insulation according Table 21. The obtained inferences from the Table 21 as follows;

- The most condensed water vapour amount was in concrete wall with internal MW in Case 2 as 23.68 kg/m^2.
- The lowest condensed water vapour amount is in concrete wall without insulation in Case 1 as 0.08 kg/m^2.
- There is no condensation risk at the concrete wall types with external insulations.
- Locating the insulation material on the outer side of the wall was more useful than on inner side of the wall.
- Also, this table showed the effect of liquid transfer and latent heat transfer at the hygrothermal behavior of the wall.
- The condensed water vapour amount in concrete wall with internal insulations is higher in Case 2 than in Case 1.

- Aerated Concrete Wall

There are condensation points in aerated concrete wall with internal XPS, EPS and MW insulation according Table 22. The obtained inferences from the Table 22 as follows;

- The most condensed water amount was in aerated concrete wall with internal MW in Case 2 as 1.62 kg/m^2.
- The lowest condensed water amount was in aerated concrete wall with external XPS in Case12 as 0.03 kg/m^2.
- Condensation takes place in all aerated concrete wall types. The condensed water does not evaporate totally at the ed of simulation time.
- Locating the insulation material on the outer side of the wall was more useful than on inner side of the wall.
- Also, this table showed the effect of liquid transfer and latent heat transfer at the hygrothermal behavior of the wall. The water content in the wall types with internal insulation in Case 2 is lower than in Case 1.
- The water content in the wall types with external insulation in Case 1 is lower than in Case 2.

Table 22. Total Water Content in Aerated Concrete Wall Types

Wall Types				**Total Water Content (kg/m^2)**				
				Start	**End**	**Min**	**Max**	**Δm**
Aerated Concrete	**EPS**	**Internal**	**Case 1**	4.51	4.90	5.33	3.64	0.39
			Case 2	4.07	4.34	4.74	3.41	0.27
			Case 3	4.07	4.33	4.73	3.42	0.27
		External	**Case 1**	4.45	4.56	5.08	3.42	0.11
			Case 2	4.14	4.31	4.81	3.31	0.17
			Case 3	4.16	4.34	4.84	3.33	0.18
	XPS	**Internal**	**Case 1**	4.20	4.41	4.81	3.42	0.20
			Case 2	3.74	3.79	4.17	3.19	0.05
			Case 3	3.75	3.79	4.18	3.19	0.05
		External	**Case 1**	4.36	4.50	5.00	3.40	0.13
			Case 2	4.05	4.28	4.75	3.33	0.23
			Case 3	4.07	4.31	4.79	3.35	0.24
	MW	**Internal**	**Case 1**	6.53	8.07	8.97	4.79	1.53
			Case 2	5.82	7.43	8.50	4.35	1.62
			Case 3	5.82	7.28	8.34	4.36	1.46
		External	**Case 1**	4.35	4.38	4.98	3.22	0.03
			Case 2	4.20	4.27	4.77	3.17	0.07
			Case 3	4.20	4.27	4.78	3.17	0.07
	Without		**Case 1**	5.22	5.61	6.23	3.92	0.38

4.4.2.4.2. Drying Time Estimation of Initial Water Content in Walls

The drying times of initial water content in walls were estimated by analyzing the relative humidity vs time figures. The graphs show the relative humidity at the monitor positions within the wall in two different conditions that are with 80% initial humidity and without initial humidity. The graphs were created for brick, concrete, aerated concrete with inner and outer XPS, EPS and MW insulations. The brick wall with XPS, concrete wall with EPS, aerated concrete wall with MW were selected to shown. The intersection of two relative humidity lines that are in with and without initial humidity defines the drying time. The monitor 3, 5 and 7 were selected to monitor positions. The drying time of brick wall with internal and external XPS is 21 months and 8 months, respectively. The other drying times of brick wall are shown in Table 24.

Figure 79. Relative Humidity at Monitor Positions within Brick Wall with Internal XPS

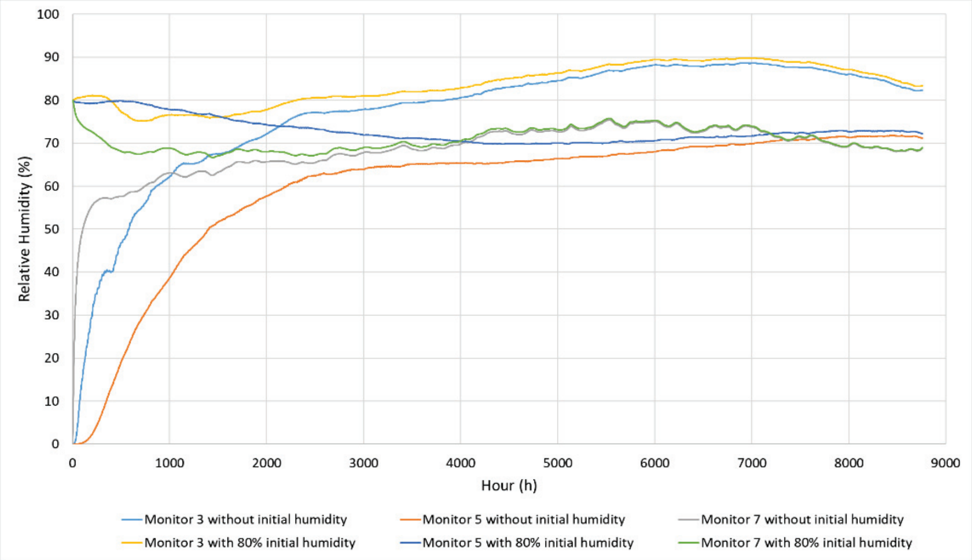


Figure 80. Relative Humidity at Monitor Positions within Brick Wall with External XPS

The monitor 3, 5 and 7 were selected to monitor positions. The drying time of concrete wall with internal and external EPS is longer than 12 months. The other drying times of concrete wall are shown in Table 24.

In concrete wall with EPS, the relative humidity lines do not intersect any points.

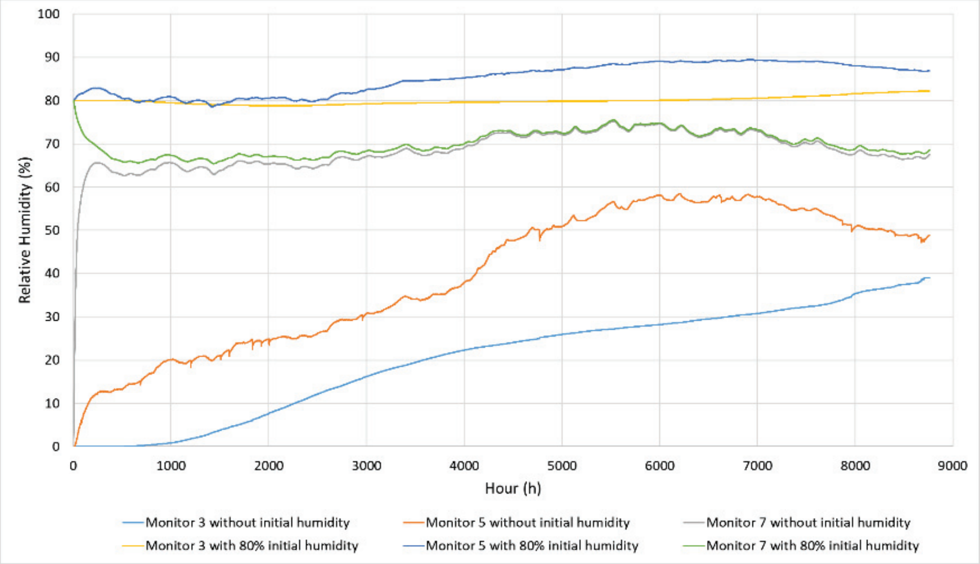


Figure 81. Relative Humidity at Monitor Positions within Concrete Wall with Internal EPS

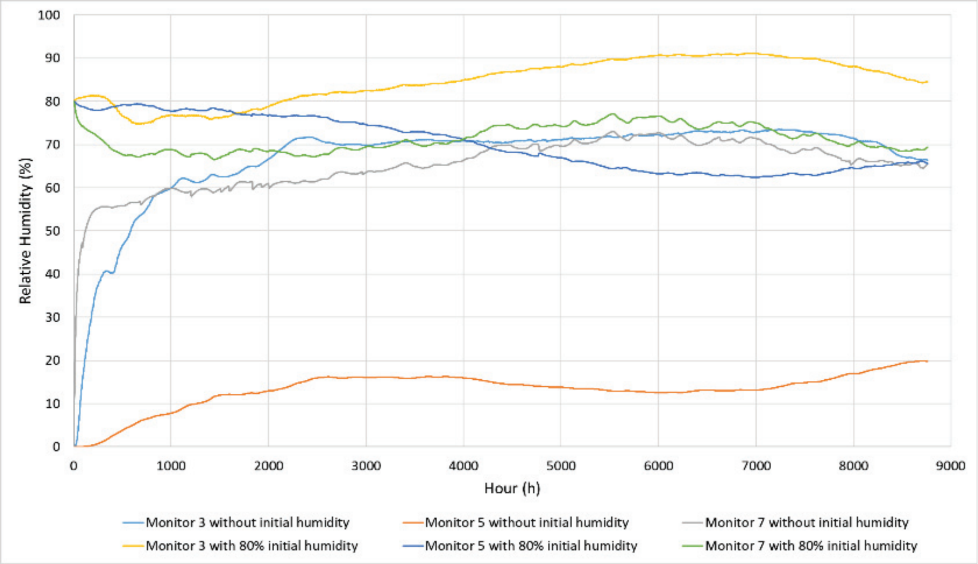


Figure 82. Relative Humidity at Monitor Positions within Concrete Wall with External EPS

The monitor 3, 5 and 7 were selected to monitor positions. The drying time of aerated concrete wall with internal and external MW is 10 and 6 months, respectively. The other drying times of aerated concrete wall are shown in Table 23.

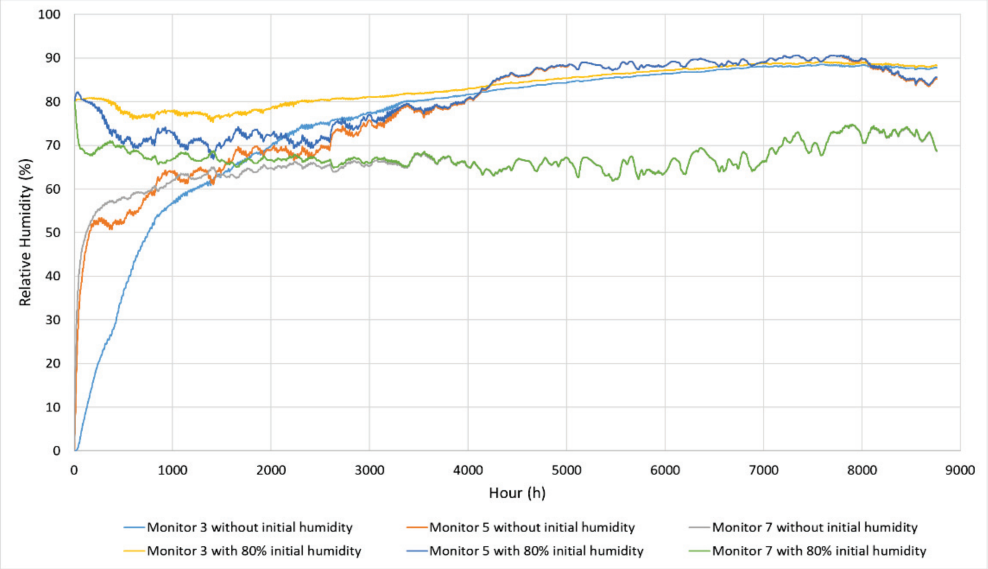


Figure 83. Relative Humidity at Monitor Positions within Aerated Concrete Wall with Internal MW

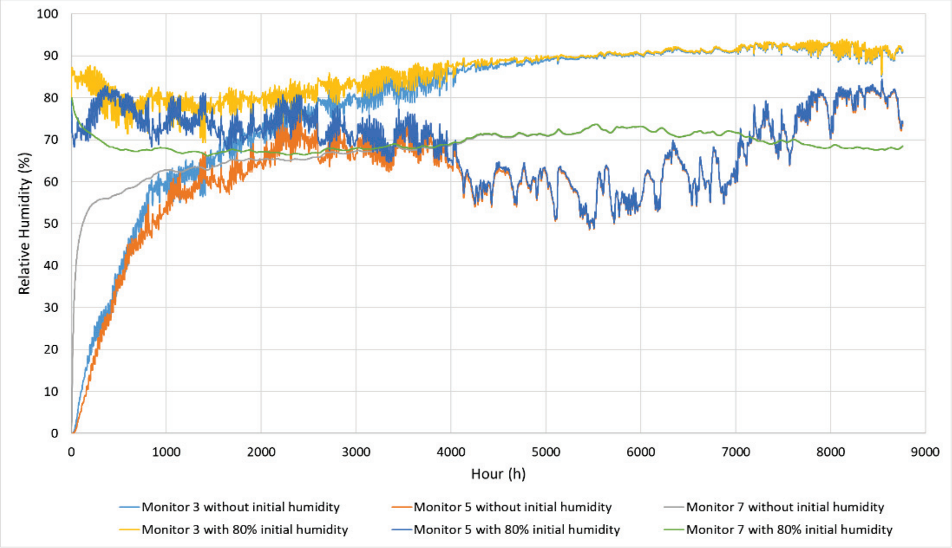


Figure 84. Relative Humidity at Monitor Positions within Aerated Concrete Wall with External MW

Table 23. Drying Time Estimations of Wall Types

Wall Types			**Drying Time**
Aerated Concrete	**EPS**	**internal**	>12 months
		external	10 months
		without	9 months
	XPS	**internal**	>12 months
		external	12 months
		without	9 months
	MW	**internal**	10 months
		external	6 months
		without	9 months
Concrete	**EPS**	**internal**	> 12 months
		external	> 12 months
		without	> 12 months
	XPS	**internal**	> 12 months
		external	> 12 months
		without	> 12 months
	MW	**internal**	> 12 months
		external	> 12 months
		without	> 12 months
Brick	**EPS**	**internal**	>12 months
		external	9 months
		without	10 months
	XPS	**internal**	>12 months
		external	12 months
		without	10 months
	MW	**internal**	5 months
		external	6 months
		without	10 months

When analyzing the Table 23, the following inferences were obtained;

- The fastest drying time is 5 months belonging to aerated concrete wall with internal XPS.
- The all wall types with MW insulation dry faster than with other insulation materials.
- The all wall types with XPS insulation dry slower than with other insulation materials.
- The all concrete walls do not dry in less than 12 months.

CHAPTER 5

CONCLUSIONS

In this study, the heat and moisture performance of the external wall types, consisted of structural body and insulation materials, were analyzed by two calculation models that are the analysis model specified in TS 825 [4] and the numerical simulation tool developed by Künzel[5]. The reason for choosing of these two analysis models is that one of them is used in our country and other is used in Europe commonly. By this study, the main goal in this thesis is to determine which method is more accurate on analyzing heat and moisture performance of the buildings. Moreover, the investigation of the differences between these two models by comparing the results and the calculation procedures is performed. Hereby, inadequacies of the analysis model used in our country would be revealed, and then the lead for the removal of these inadequacies is taken. Also, the analysis showed the effects of the wall body material and the type and the location of the insulation materials on the heat and moisture performance of the wall.

One of the methods stated in Chapter 4.4.1. analyzes the condensation in steady condition (Glaser method) and the other one stated in Chapter 4.4.2 examines the hygrothermal performance of the external wall in transient regime (WUFI Pro 5.3). In Glaser method, only vapour diffusion is regarded, the capillary condensation is not counted in. Also, the heat and moisture transfer were evaluated independently of each other. As for the WUFI Pro simulation model, can consider all the parameters of water vapour diffusion, capillary conduction and surface diffusion. Also, this simulation program provides us with choosing proper an option evaluation of heat and moisture transfer together or separately.

Wall types were specified to analyze the condensation risk control at the walls. The 21 wall types were formed by using cement plaster, lime plaster, 3 different wall body elements (brick, concrete and aerated concrete) and 3 different insulation materials (XPS, EPS and MW) with 3 different insulation situations (internal, external and without).

Initially, the wall sections were examined by the model specified in TS 825 Directive on the Thermal Insulation in Buildings which is based on Glaser calculation. After calculating the required insulation thickness, the walls were analyzed with different insulation conditions. The graphs consisted of partial water vapour pressure vs Sd and saturated water vapor pressure vs Sd for all wall types in all months of a year. If the saturated water vapour pressure passes the partial water vapor pressure at any interface it means, there is a condensation at this layer.

According to the results of the first calculation model, aerated concrete gives the best result in temperature values in non-insulated wall sections owing to the lowest thermal conductivity value (k) among building elements. Insulated wall types give better results than non-insulated wall types. Type of insulation materials does not affect the temperature distribution largely. Condensation takes place in all wall types without insulation and occurs in all wall types with internal insulations except concrete wall with MW. Also, condensation does not occur in concrete wall with external insulation and brick wall. All wall types except brick wall with internal XPS do not pose a problem in terms of moisture. In this brick wall type, the amount of condensed water vapor is 0.446 kg/m^2 at the end of a year. So, there is a risk that moisture problems can occur such as mould growth, freezing, and wizening in the materials at the brick wall with XPS.

There is condensation in all aerated concrete wall types but the condensed water vapour evaporated at the end of a year. This situation is derived from the low water vapor diffusion factor- μ of the aerated concrete wall.

The using insulation material is needed for thermal performance of the wall. Also, the location of insulation material within the wall has a significant role in terms of moisture performance of the wall.

Secondly, the wall sections were examined by WUFI Pro that is numerical simulation tool. The same wall sections were analyzed in 3 different calculation cases with this simulation program. These cases explained in Page 64 shows the effect of capillary conduction and latent heat evaporation on the hygrothermal behavior of the wall. Also, two different analyses are done in the simulation program. One of them is determining the condensation risk and location within the wall, and the other is the drying time estimation of initial water content in the wall.

According to the simulation results, aerated concrete gives the best result in temperature values in non-insulated wall sections owing to the lowest thermal conductivity value (k) among building elements like the previous calculation model. Insulated wall types give better results than non-insulated wall types like to calculation model specified in TS 825.

Condensation occurs in all wall types without insulation in all cases. The lowest condensed water amount in concrete, aerated concrete, and brick, respectively. This situation is derived from the low water vapor diffusion factor μ of materials and porosity values. In all wall types with external insulations in all cases, condensation does not take place in there except the aerated concrete wall. There is condensation in all types of aerated concrete walls in all cases. The condensed water is higher in the types of walls with internal MW in all cases than other insulation materials. The condensed water is lower in the types of walls with internal XPS in all cases than other insulation materials.

The second analysis in the WUFI Pro. simulation program is drying time estimation of the initial water content of the wall. The all types of walls with MW insulations dry faster than with other insulation materials. The drying time of all types of concrete wall is longer than 12 months. Also, the aerated concrete with internal XPS and brick wall with internal XPS do not dry in less than 12 months. The aerated concrete wall dries faster than the others in un-insulated situation. The external insulated wall types dry faster than the internal insulated wall types.

The results of all types of the wall with internal insulations were examined in WUFI Bio, there are no problem in terms of mould formation.

Since energy saving is very important today, the building envelope has a part in energy efficiency in the building structure. Designing the building envelope having high hygrothermal performance is most need in the construction sector. If the moisture problems in the building wall can be foreseen with these analyses, saving time and cost to designer and occupants would be provided. For this situation, using realist and easy to use calculation method is very important. In this thesis, the results of two different calculation models were compared and then some differences between these models were obtained.

Table 24 shows that the two simulation models give very similar results in terms of the occurrence of condensation but the amount of condensed water vapor in the wall is different for each wall type in these two models at the end of the analysis. It is because WUFI takes into account the load of the sun, the rain, and the wind, while the model specified in TS 825 takes care only the vapor diffusion. It has been observed that the type of insulation material is not very effective on moisture performance, but its location is very effective. For this reason, the most useful material should be selected in terms of heat transition and should be positioned in the most suitable place in the wall section for the high hygrothermal performance. Diffusion resistance of the materials in a wall should be sorted from high to low according to the direction of decreasing temperature. The type of building body element plays a very critical role in terms of the condensation; therefore, the material should be selected by looking at the value of diffusion resistance factor of the material. If the wall without insulation is needed, the aerated concrete wall concrete wall and brick wall should be selected in terms of calculation results in WUFI, respectively. The moisture risk graphs are given Appendix G, K and O.

Table 24. Comparison between results of Glaser and WUFI Pro

Insulation System	Wall	Glaser Method in TS 825			WUFI Pro 5.3		
		XPS	EPS	MW	XPS	EPS	MW
Internal	Brick	+	+	+	+	+	+
	Concrete	+	+	-	+	+	+
	Aerated Concrete	+	+	+	+	+	+
External	Brick	-	-	+	-	-	-
	Concrete	-	-	-	-	-	-
	Aerated Concrete	+	+	+	+	+	+
Without	Brick	+	+	+	+	+	+
	Concrete	+	+	+	+	+	+
	Aerated Concrete	+	+	+	+	+	+

According to analysis, the calculation method specified in TS 825 gives limited information about the hygrothermal analysis than WUFI Pro 5.3 simulation program. The calculation method specified in TS 825 analyzes the only condensation and mould risk. Besides, WUFI Pro dynamic simulation program analyzes the interstitial condensation in transient regime, the effects of capillary action and solar radiation on the vapour migration, drying time estimation of the wall structure. If fast and sciolism information is desired, this program should be used; more detailed information desired, the WUFI computer program should be used. If it is desired to obtain correct data, it can be obtained by entering the most realistic data in WUFI simulation program.

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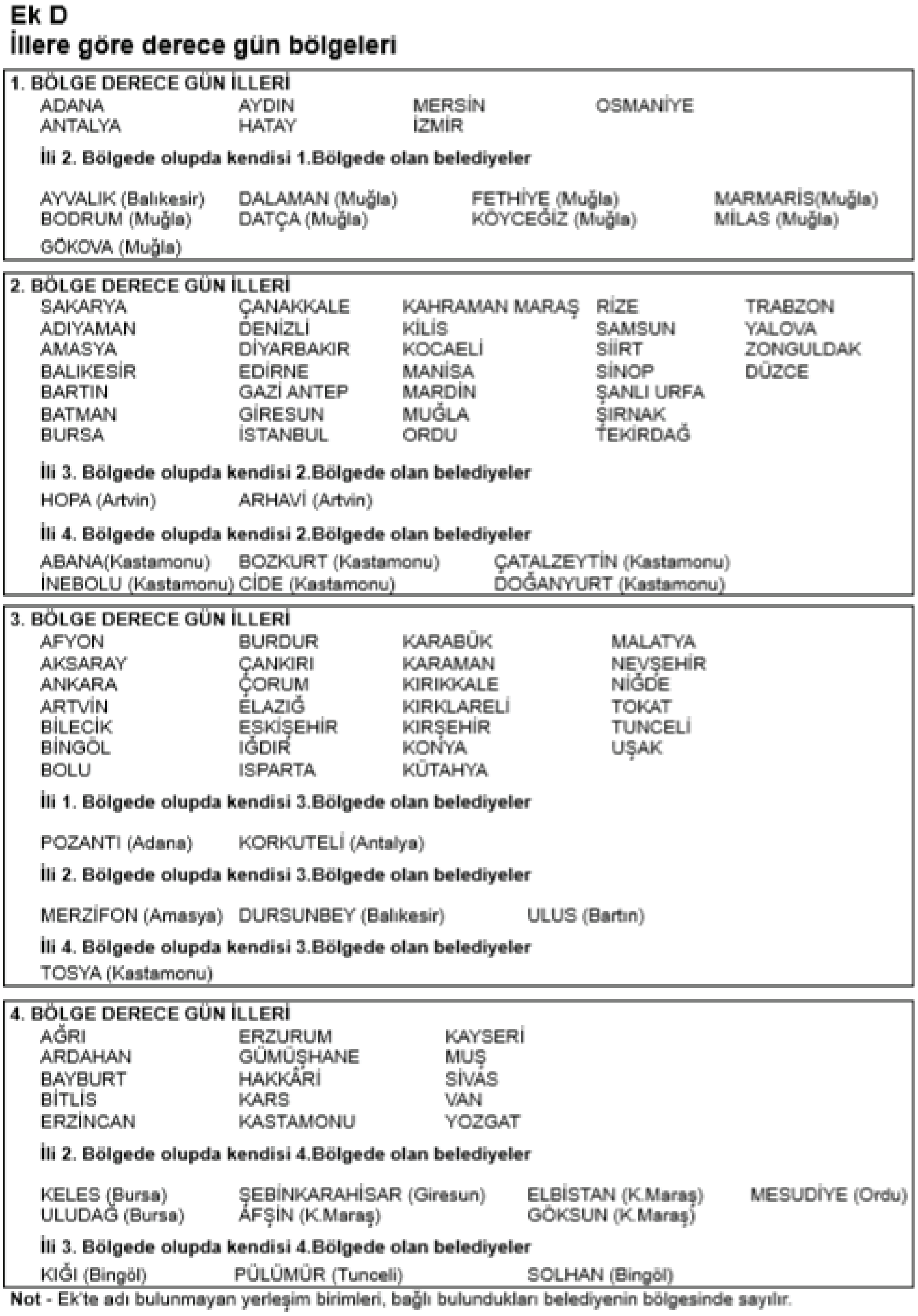
APPENDIX A

SPECIFIED U_w VALUES ACCORDING TO DEGREE ZONES

Zone	U_{wall}	$U_{ceiling}$	U_{floor}	U_{window}
1	0.70	0.45	0.70	2.4
2	0.60	0.40	0.60	2.4
3	0.50	0.30	0.45	2.4
4	0.40	0.25	0.40	2.4

APPENDIX B

DEGREE DAY ZONES SPECIFIED IN TS 825 BY PROVINCES



Ek D

İllere göre derece gün bölgeleri

1. BÖLGE DERECE GÜN İLLERİ

ADANA
ANTALYA
AYDIN
HATAY
MERSİN
İZMİR
OSMANİYE

İli 2. Bölgede olupda kendisi 1.Bölgede olan belediyeler

AYVALIK (Balıkesir)
BODRUM (Muğla)
GÖKOVA (Muğla)
DALAMAN (Muğla)
DATÇA (Muğla)
FETHİYE (Muğla)
KÖYCEĞİZ (Muğla)
MARMARİS(Muğla)
MİLAS (Muğla)

2. BÖLGE DERECE GÜN İLLERİ

SAKARYA
ADIYAMAN
AMASYA
BALIKESİR
BARTIN
BATMAN
BURSA
ÇANAKKALE
DENİZLİ
DİYARBAKIR
EDİRNE
GAZİ ANTEP
GİRESUN
İSTANBUL
KAHRAMAN MARAŞ
KİLİS
KOCAELİ
MANİSA
MARDİN
MUĞLA
ORDU
RİZE
SAMSUN
SİİRT
SİNOP
ŞANLI URFA
ŞIRNAK
TEKİRDAĞ
TRABZON
YALOVA
ZONGULDAK
DÜZCE

İli 3. Bölgede olupda kendisi 2.Bölgede olan belediyeler

HOPA (Artvin)
ARHAVİ (Artvin)

İli 4. Bölgede olupda kendisi 2.Bölgede olan belediyeler

ABANA(Kastamonu)
İNEBOLU (Kastamonu)
BOZKURT (Kastamonu)
CİDE (Kastamonu)
ÇATALZEYTİN (Kastamonu)
DOĞANYURT (Kastamonu)

3. BÖLGE DERECE GÜN İLLERİ

AFYON
AKSARAY
ANKARA
ARTVİN
BİLECİK
BİNGÖL
BOLU
BURDUR
ÇANKIRI
ÇORUM
ELAZIĞ
ESKİŞEHİR
IĞDIR
ISPARTA
KARABÜK
KARAMAN
KIRIKKALE
KIRKLARELİ
KIRŞEHİR
KONYA
KÜTAHYA
MALATYA
NEVŞEHİR
NİĞDE
TOKAT
TUNCELİ
UŞAK

İli 1. Bölgede olupda kendisi 3.Bölgede olan belediyeler

POZANTI (Adana)
KORKUTELİ (Antalya)

İli 2. Bölgede olupda kendisi 3.Bölgede olan belediyeler

MERZİFON (Amasya)
DURSUNBEY (Balıkesir)
ULUS (Bartın)

İli 4. Bölgede olupda kendisi 3.Bölgede olan belediyeler

TOSYA (Kastamonu)

4. BÖLGE DERECE GÜN İLLERİ

AĞRI
ARDAHAN
BAYBURT
BİTLİS
ERZİNCAN
ERZURUM
GÜMÜŞHANE
HAKKÂRİ
KARS
KASTAMONU
KAYSERİ
MUŞ
SİVAS
VAN
YOZGAT

İli 2. Bölgede olupda kendisi 4.Bölgede olan belediyeler

KELES (Bursa)
ULUDAĞ (Bursa)
ŞEBİNKARAHİSAR (Giresun)
AFŞİN (K.Maraş)
ELBİSTAN (K.Maraş)
GÖKSUN (K.Maraş)
MESUDİYE (Ordu)

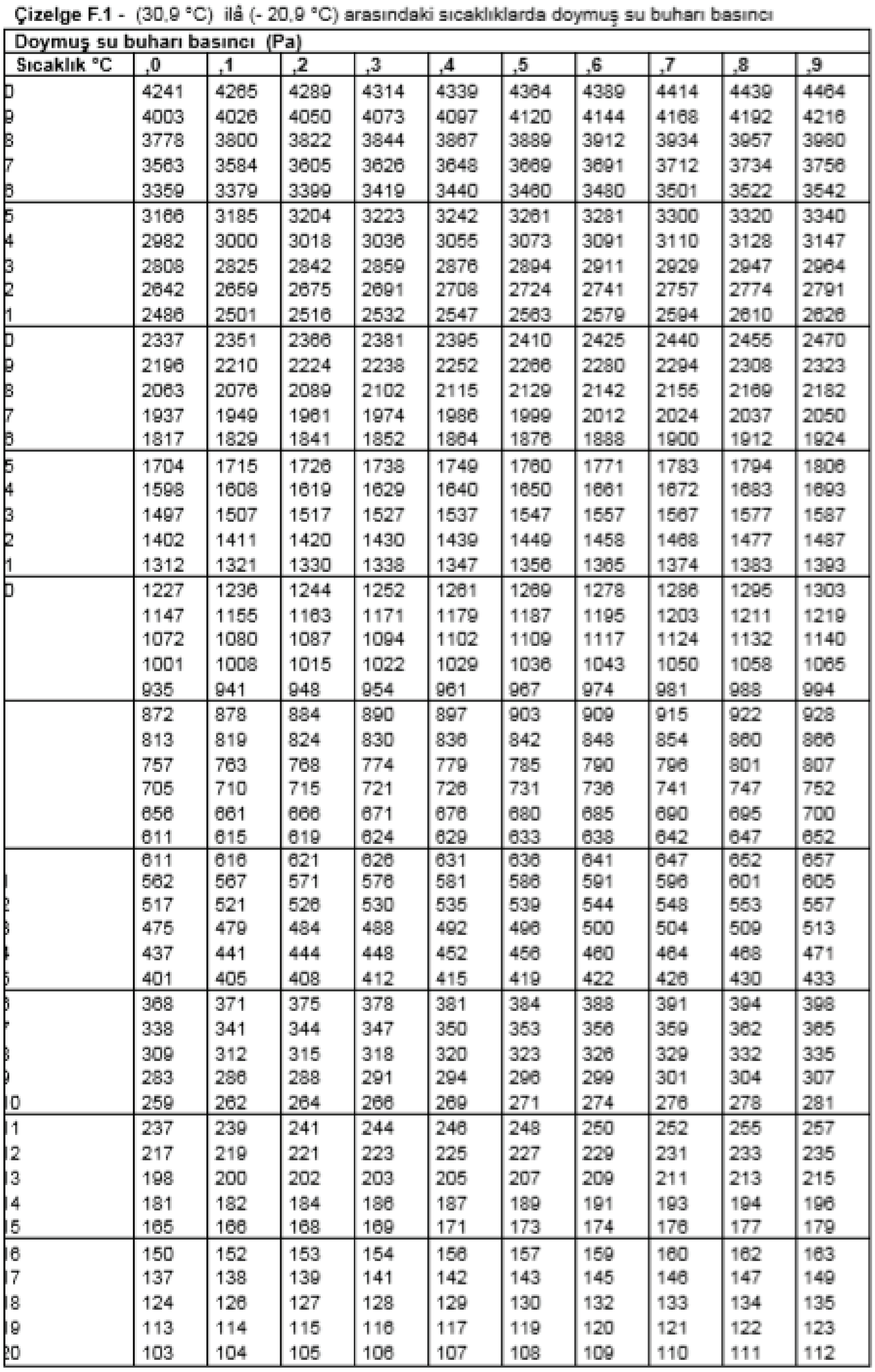
İli 3. Bölgede olupda kendisi 4.Bölgede olan belediyeler

KIĞI (Bingöl)
PÜLÜMÜR (Tunceli)
SOLHAN (Bingöl)

Not - Ek'te adı bulunmayan yerleşim birimleri, bağlı bulundukları belediyenin bölgesinde sayılır.

APPENDIX C

THE TABLE OF SATURATED WATER VAPOR PRESSURE AS A FUNCTION OF TEMPERATURE



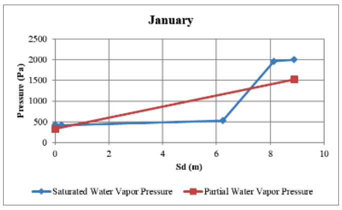
Çizelge F.1 - (30,9 °C) ilâ (- 20,9 °C) arasındaki sıcaklıklarda doymuş su buharı basıncı

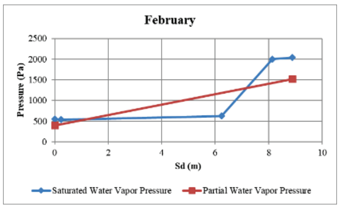
Doymuş su buharı basıncı (Pa)

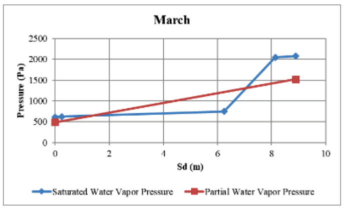
Sıcaklık °C	**,0**	**,1**	**,2**	**,3**	**,4**	**,5**	**,6**	**,7**	**,8**	**,9**
0	4241	4265	4289	4314	4339	4364	4389	4414	4439	4464
9	4003	4026	4050	4073	4097	4120	4144	4168	4192	4216
8	3778	3800	3822	3844	3867	3889	3912	3934	3957	3980
7	3563	3584	3605	3626	3648	3669	3691	3712	3734	3756
6	3359	3379	3399	3419	3440	3460	3480	3501	3522	3542
5	3166	3185	3204	3223	3242	3261	3281	3300	3320	3340
4	2982	3000	3018	3036	3055	3073	3091	3110	3128	3147
3	2808	2825	2842	2859	2876	2894	2911	2929	2947	2964
2	2642	2659	2675	2691	2708	2724	2741	2757	2774	2791
1	2486	2501	2516	2532	2547	2563	2579	2594	2610	2626
0	2337	2351	2366	2381	2395	2410	2425	2440	2455	2470
9	2196	2210	2224	2238	2252	2266	2280	2294	2308	2323
8	2063	2076	2089	2102	2115	2129	2142	2155	2169	2182
7	1937	1949	1961	1974	1986	1999	2012	2024	2037	2050
6	1817	1829	1841	1852	1864	1876	1888	1900	1912	1924
5	1704	1715	1726	1738	1749	1760	1771	1783	1794	1806
4	1598	1608	1619	1629	1640	1650	1661	1672	1683	1693
3	1497	1507	1517	1527	1537	1547	1557	1567	1577	1587
2	1402	1411	1420	1430	1439	1449	1458	1468	1477	1487
1	1312	1321	1330	1338	1347	1356	1365	1374	1383	1393
0	1227	1236	1244	1252	1261	1269	1278	1286	1295	1303
	1147	1155	1163	1171	1179	1187	1195	1203	1211	1219
	1072	1080	1087	1094	1102	1109	1117	1124	1132	1140
	1001	1008	1015	1022	1029	1036	1043	1050	1058	1065
	935	941	948	954	961	967	974	981	988	994
	872	878	884	890	897	903	909	915	922	928
	813	819	824	830	836	842	848	854	860	866
	757	763	768	774	779	785	790	796	801	807
	705	710	715	721	726	731	736	741	747	752
	656	661	666	671	676	680	685	690	695	700
	611	615	619	624	629	633	638	642	647	652
	611	616	621	626	631	636	641	647	652	657
1	562	567	571	576	581	586	591	596	601	605
2	517	521	526	530	535	539	544	548	553	557
3	475	479	484	488	492	496	500	504	509	513
4	437	441	444	448	452	456	460	464	468	471
5	401	405	408	412	415	419	422	426	430	433
6	368	371	375	378	381	384	388	391	394	398
7	338	341	344	347	350	353	356	359	362	365
8	309	312	315	318	320	323	326	329	332	335
9	283	286	288	291	294	296	299	301	304	307
10	259	262	264	266	269	271	274	276	278	281
11	237	239	241	244	246	248	250	252	255	257
12	217	219	221	223	225	227	229	231	233	235
13	198	200	202	203	205	207	209	211	213	215
14	181	182	184	186	187	189	191	193	194	196
15	165	166	168	169	171	173	174	176	177	179
16	150	152	153	154	156	157	159	160	162	163
17	137	138	139	141	142	143	145	146	147	149
18	124	126	127	128	129	130	132	133	134	135
19	113	114	115	116	117	119	120	121	122	123
20	103	104	105	106	107	108	109	110	111	112

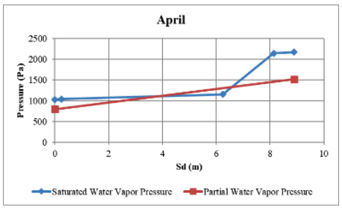
APPENDIX D

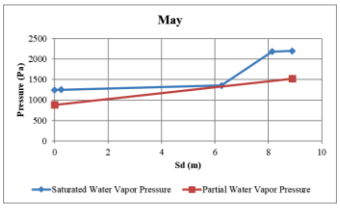
DIFFUSION CONTROL GRAPHS OF BRICK WALL WITH INTERNAL XPS

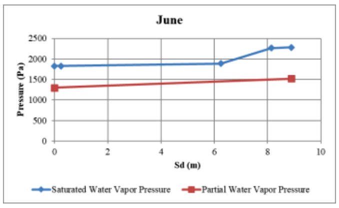


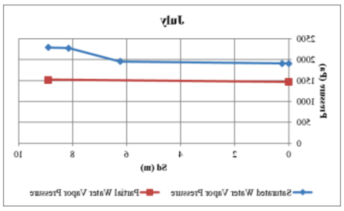


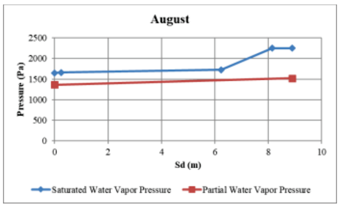


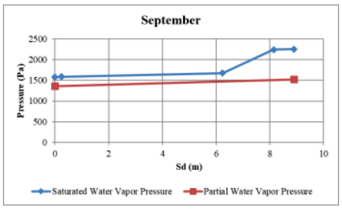


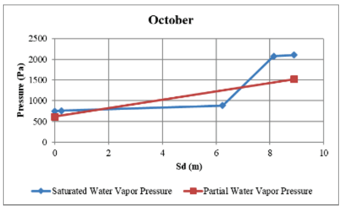


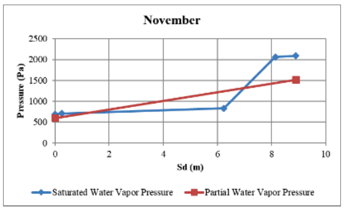


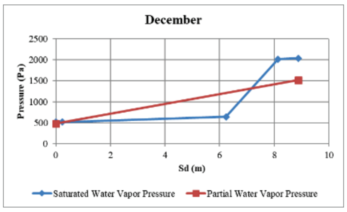




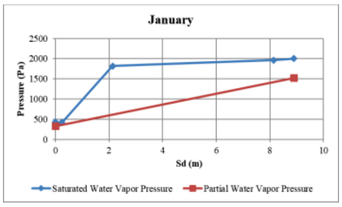


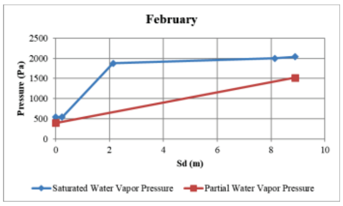


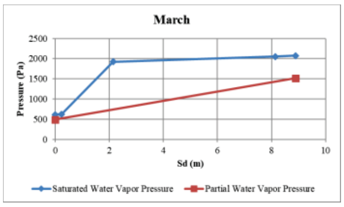


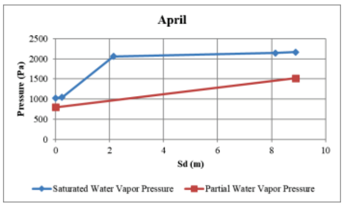


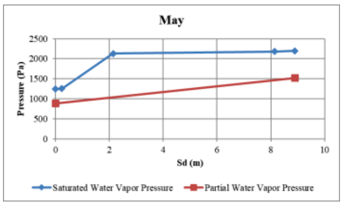
DIFFUSION CONTROL GRAPHS OF BRICK WALL WITH INTERNAL XPS

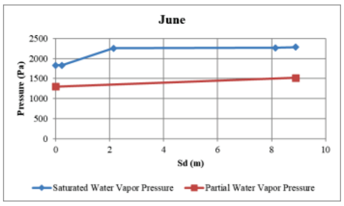


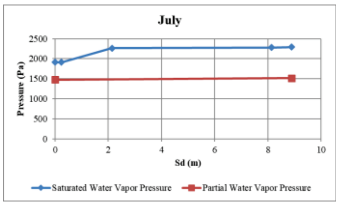


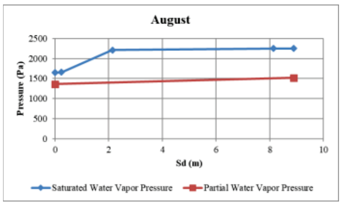


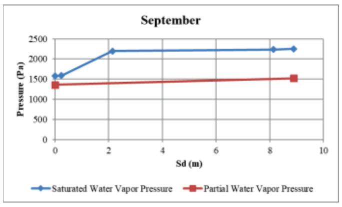


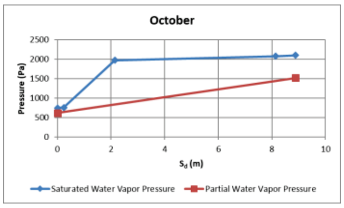


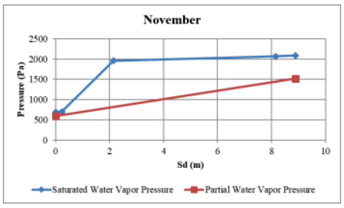


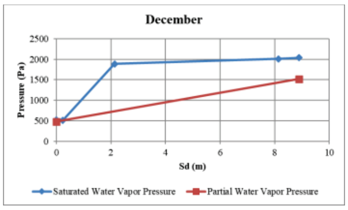












APPENDIX E

THE TABLES OF THE CONDENSED WATER VAPOUR AMOUNT IN BRICK WALL WITH EPS

Brick Wall with Internal EPS				
	$T_{outdoor}$ (^{0}C)	$RH_{outdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
November	1.62	88	0.082	0.082
December	-2.61	89	0.155	0.236
January	-6.22	88	0.150	0.386
February	-3.07	84	0.167	0.553
March	-0.12	80	0.113	0.666
April	7.31	78	0.012	0.679
May	10.11	72	-0.096	0.583
June	16.10	71	-0.187	0.395
July	16.80	77	-0.317	0.078
August	14.47	83	-0.322	-0.244
September	13.80	81	-0.153	-0.396
October	2.62	84	-0.094	-0.490

Brick Wall with External EPS				
	$T_{outdoor}$ (^{0}C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
January	-6.22	88	0	0
February	-3.07	84	0	0
March	-0.12	80	0	0
April	7.31	78	0	0
May	10.11	72	0	0
June	16.10	71	0	0
July	16.80	77	0	0
August	14.47	83	0	0
September	13.80	81	0	0
October	2.62	84	0	0
November	1.62	88	0	0
December	-2.61	89	0	0

APPENDIX F

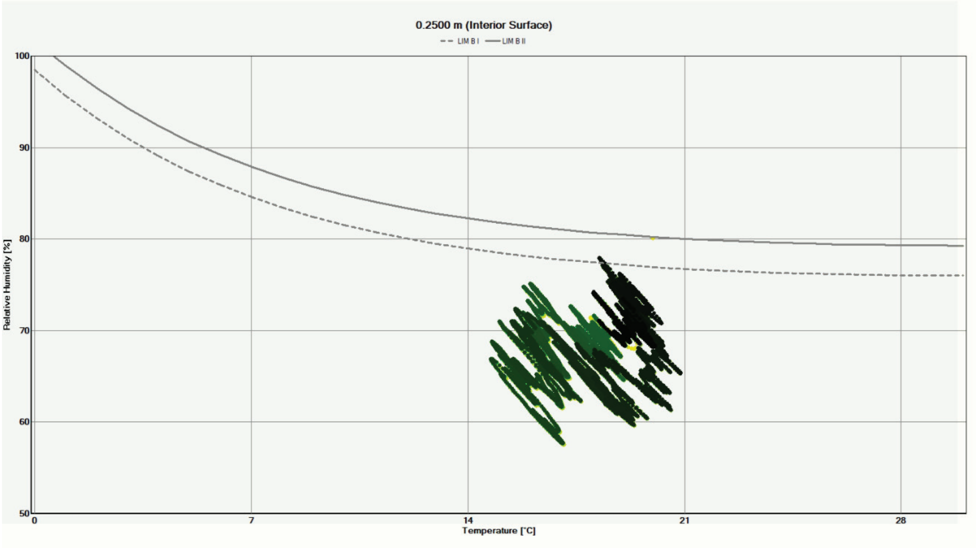
THE TABLES OF THE CONDENSED WATER VAPOUR AMOUNT IN BRICK WALL WITH MW

Brick Wall with Internal MW				
	$T_{outdoor}$ (^{0}C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
December	-2.61	89	0.113	0.113
January	-6.22	88	0.013	0.126
February	-3.07	84	-0.119	0.007
March	-0.12	80	-0.117	-0.110
April	7.31	78	-0.441	-0.551
May	10.11	72	-0.745	-1.296
June	16.10	71	-1.203	-2.498
July	16.80	77	-1.017	-3.515
August	14.47	83	-0.673	-4.189
September	13.80	81	-0.508	-4.696
October	2.62	84	-0.152	-4.849
November	1.62	88	-0.073	-4.922

Brick Wall with External MW				
	$T_{outdoor}$ (^{0}C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
December	-2.61	89	0.113	0.113
January	-6.22	88	0.013	0.126
February	-3.07	84	-0.119	0.007
March	-0.12	80	-0.117	-0.110
April	7.31	78	-0.441	-0.551
May	10.11	72	-0.745	-1.296
June	16.10	71	-1.203	-2.498
July	16.80	77	-1.017	-3.515
August	14.47	83	-0.673	-4.189
September	13.80	81	-0.508	-4.696
October	2.62	84	-0.152	-4.849
November	1.62	88	-0.073	-4.922

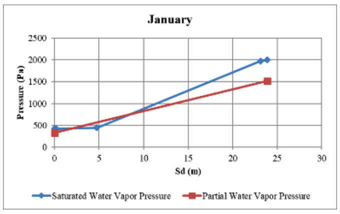
APPENDIX G

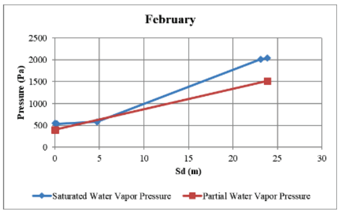
MOISTURE RISK GRAPHS OF BRICK WALL WITHOUT INSULATION

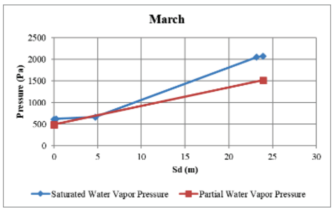


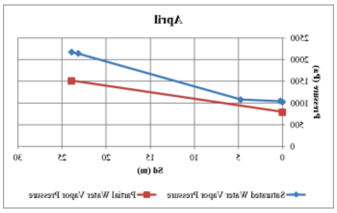
APPENDIX H

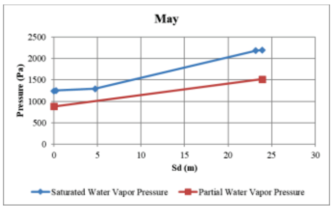
DIFFUSION CONTROL GRAPHS OF CONCRETE WALL WITH INTERNAL XPS

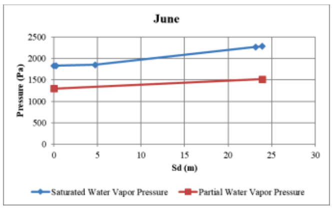


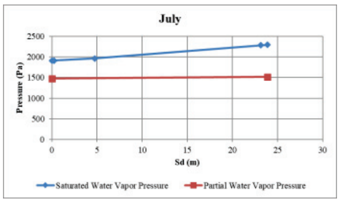


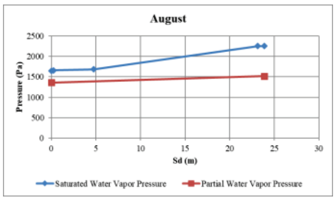


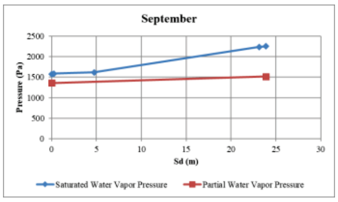


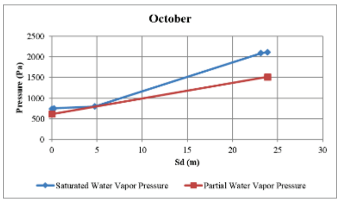


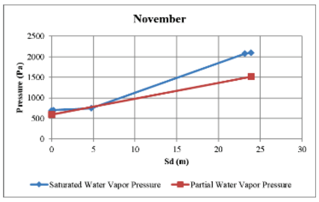


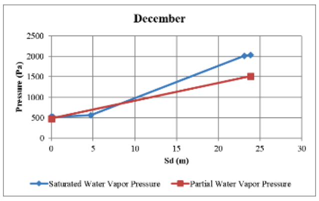




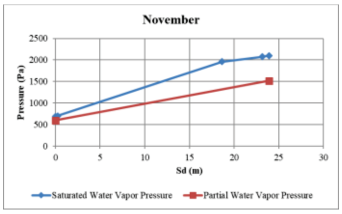


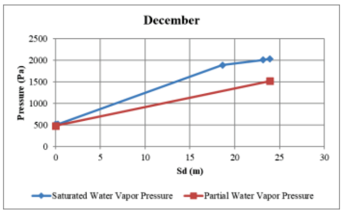


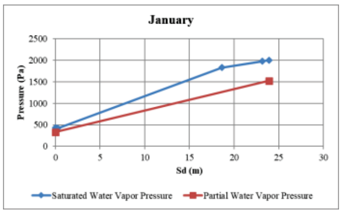


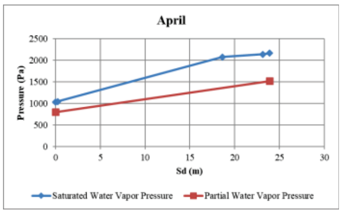


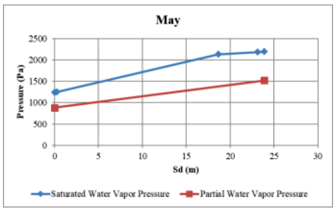
DIFFUSION CONTROL GRAPHS OF CONCRETE WALL WITH INTERNAL XPS

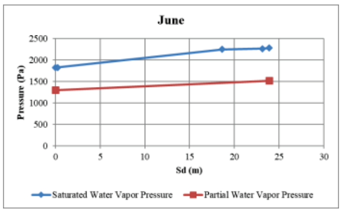


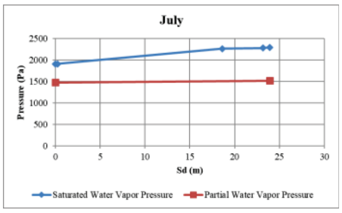


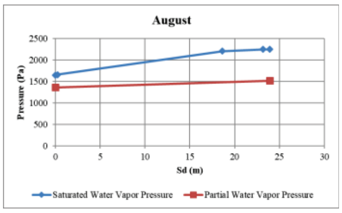


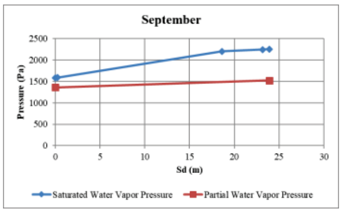


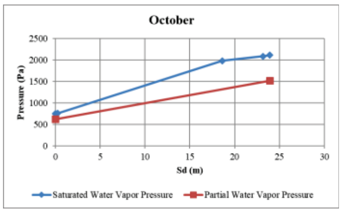


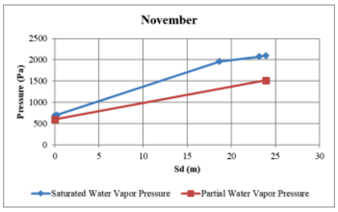


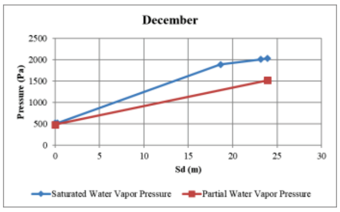












APPENDIX I

THE TABLE OF CONDENSED WATER VAPOUR AMOUNT IN CONCRETE WALL WITH XPS

Concrete Wall with Internal XPS				
	$T_{outdoor}$ (^0C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
October	2.62	84	0.007	0.007
November	1.62	88	0.010	0.017
December	-2.61	89	0.020	0.038
January	-6.22	88	0.020	0.058
February	-3.07	84	0.012	0.069
March	-0.12	80	0.011	0.080
April	7.31	78	-0.008	0.072
May	10.11	72	-0.022	0.049
June	16.10	71	-0.049	0.001
July	16.80	77	-0.044	-0.044
August	14.47	83	-0.027	-0.071
September	13.80	81	-0.021	-0.093

Concrete Wall with External XPS				
	$T_{outdoor}$ (^0C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
January	2.62	84	0	0
February	1.62	88	0	0
March	-2.61	89	0	0
April	-6.22	88	0	0
May	-3.07	84	0	0
June	-0.12	80	0	0
July	7.31	78	0	0
August	10.11	72	0	0
September	16.10	71	0	0
October	16.80	77	0	0
November	14.47	83	0	0
December	13.80	81	0	0

APPENDIX J

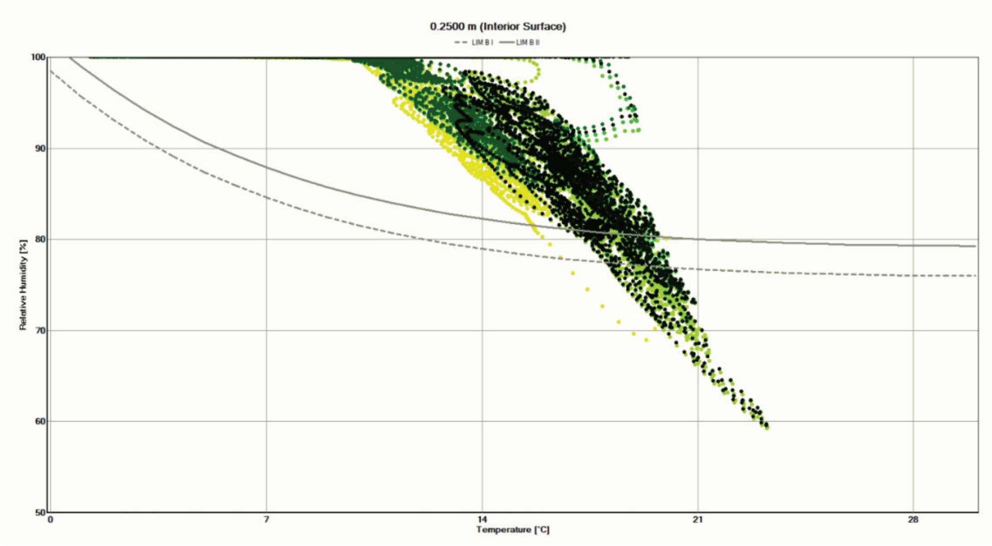
THE TABLE OF CONDENSED WATER VAPOUR AMOUNT IN CONCRETE WALL WITH MW

Concrete Wall with Internal MW				
	$T_{outdoor}$ (^0C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
January	-6.22	88	0	0
February	-3.07	84	0	0
March	-0.12	80	0	0
April	7.31	78	0	0
May	10.11	72	0	0
June	16.10	71	0	0
July	16.80	77	0	0
August	14.47	83	0	0
September	13.80	81	0	0
October	2.62	84	0	0
November	1.62	88	0	0
December	-2.61	89	0	0

Concrete Wall with External MW				
	$T_{outdoor}$ (^0C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
January	-6.22	88	0	0
February	-3.07	84	0	0
March	-0.12	80	0	0
April	7.31	78	0	0
May	10.11	72	0	0
June	16.10	71	0	0
July	16.80	77	0	0
August	14.47	83	0	0
September	13.80	81	0	0
October	2.62	84	0	0
November	1.62	88	0	0
December	-2.61	89	0	0

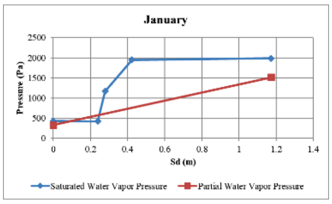
APPENDIX K

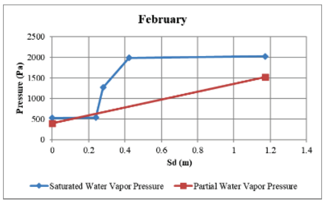
DIFFUSION CONTROL GRAPHS OF CONCRETE WALL WITHOUT INSULATION

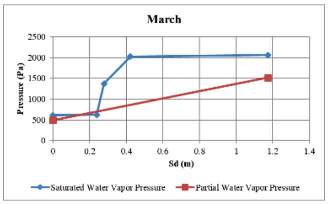


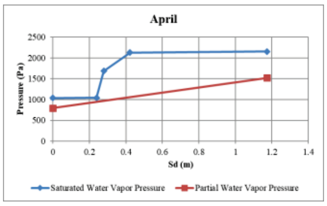
APPENDIX L

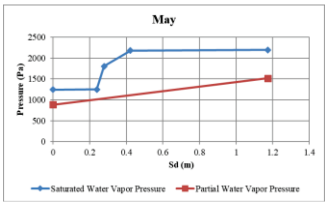
DIFFUSION CONTROL GRAPHS OF AERATED CONCRETE WALL WITH INTERNAL MW

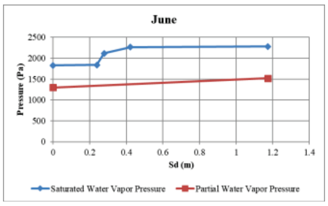


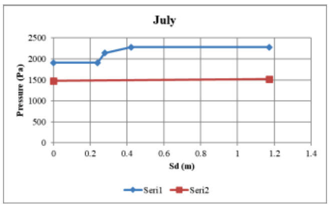


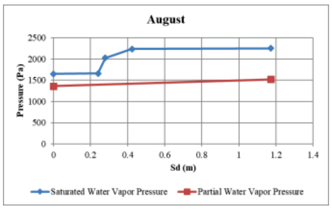


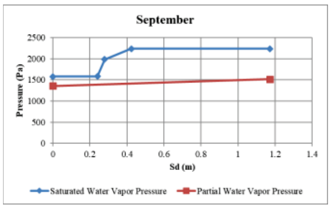


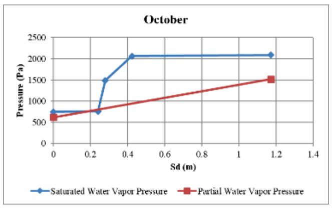


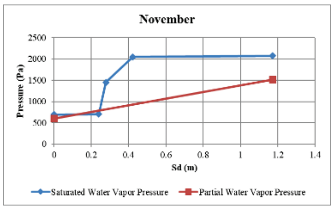


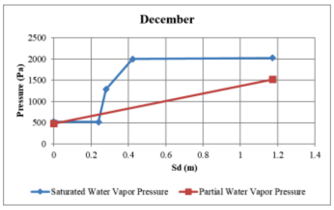




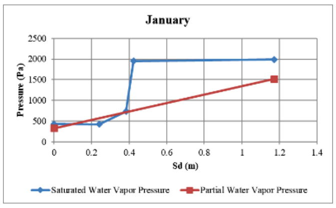


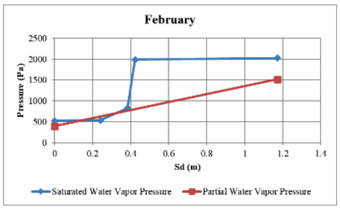


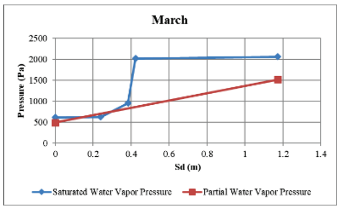


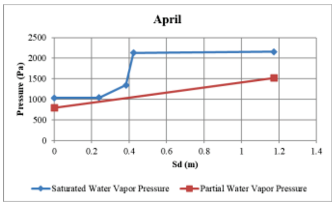


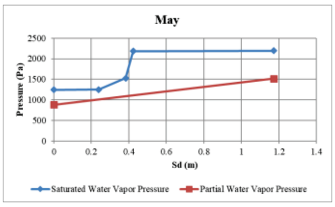
DIFFUSION CONTROL GRAPHS OF AERATED CONCRETE WALL WITH EXTERNAL MW

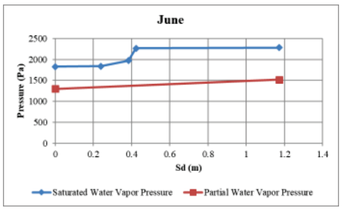

January

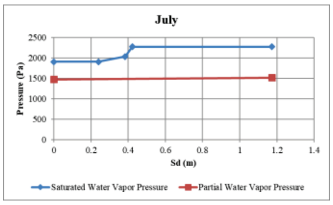

February

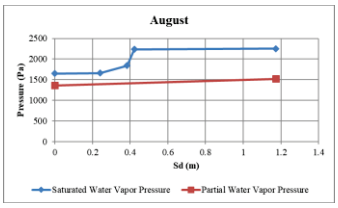

March

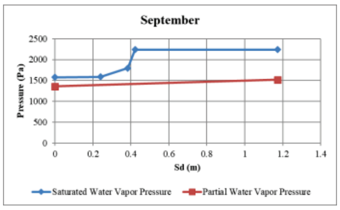

April

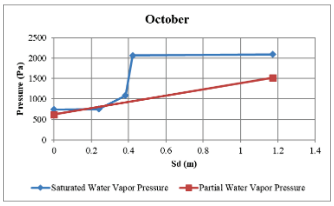

May

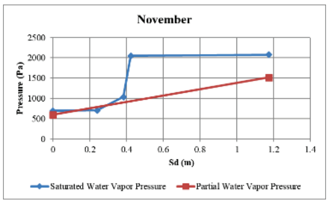

June

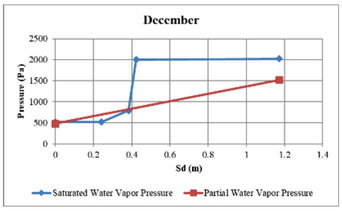

July


August


September


October


November


December

APPENDIX M

THE TABLE OF CONDENSED WATER AMOUNT IN AERATED CONCRETE WALL WITH EPS

Aerated Concrete Wall with Internal EPS				
	$T_{outdoor}$ (^0C)	$RH_{outdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
December	-2.61	89	0.141	0.141
January	-6.22	88	0.044	0.185
February	-3.07	84	-0.091	0.094
March	-0.12	80	-0.092	0.003
April	7.31	78	-0.427	-0.425
May	10.11	72	-0.737	-1.162
June	16.10	71	-1.240	-2.402
July	16.80	77	-1.028	-3.430
August	14.47	83	-0.677	-4.108
September	13.80	81	-0.510	-4.617
October	2.62	84	-0.131	-4.748
November	1.62	88	-0.174	-4.922

Aerated Concrete Wall with External EPS				
	$T_{outdoor}$ (^0C)	$RH_{outdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
December	-2.61	89	0.141	0.141
January	-6.22	88	0.044	0.185
February	-3.07	84	-0.091	0.094
March	-0.12	80	-0.092	0.003
April	7.31	78	-0.427	-0.425
May	10.11	72	-0.737	-1.162
June	16.10	71	-1.240	-2.402
July	16.80	77	-1.028	-3.430
August	14.47	83	-0.677	-4.108
September	13.80	81	-0.510	-4.617
October	2.62	84	-0.131	-4.748
November	1.62	88	-0.174	-4.922

APPENDIX N

THE TABLE OF CONDENSED WATER AMOUNT IN AERATED CONCRETE WALL WITH XPS

Aerated Concrete Wall with Internal XPS

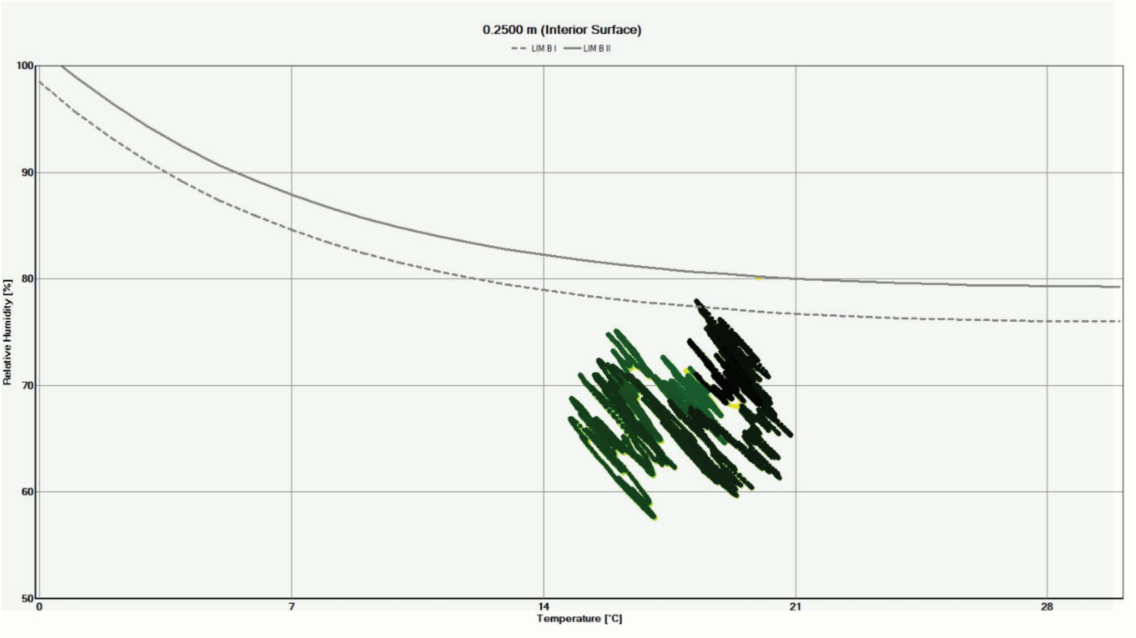
	$T_{outdoor}$ (^{0}C)	$R_{Houtdoor}$ (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
December	-2.61	89	0.080	0.080
January	-6.22	88	0.090	0.170
February	-3.07	84	0.078	0.248
March	-0.12	80	0.008	0.256
April	7.31	78	-0.181	0.075
May	10.11	72	-0.272	-0.197
June	16.10	71	-0.457	-0.654
July	16.80	77	-0.458	-1.112
August	14.47	83	-0.371	-1.483
September	13.80	81	-0.344	-1.827
October	2.62	84	-0.051	-1.877
November	1.62	88	-0.026	-1.904

Aerated Concrete Wall with External XPS

	Toutdoor (^{0}C)	$R_h$outdoor (%)	m_y (kg/m^2)	Σm_y (kg/m^2)
December	-2.61	89	0.057	0.057
January	-6.22	88	-0.054	0.003
February	-3.07	84	-0.173	-0.170
March	-0.12	80	-0.166	-0.336
April	7.31	78	-0.467	-0.803
May	10.11	72	-0.760	-1.563
June	16.10	71	-1.186	-2.748
July	16.80	77	-0.968	-3.716
August	14.47	83	-0.666	-4.382
September	13.80	81	-0.504	-4.886
October	2.62	84	-0.194	-5.080
November	1.62	88	-0.118	-5.198

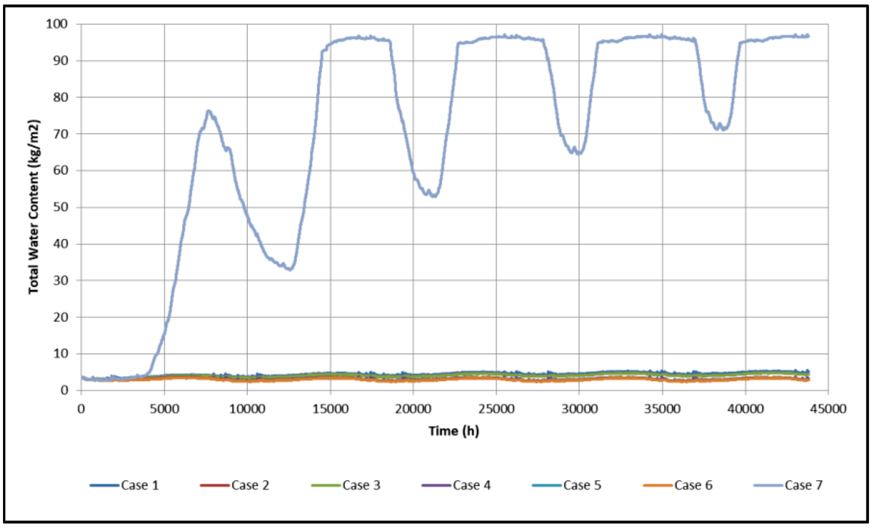
APPENDIX O

DIFFUSION CONTROL GRAPHS OF AERATED CONCRETE WALL WITHOUT INSULATION

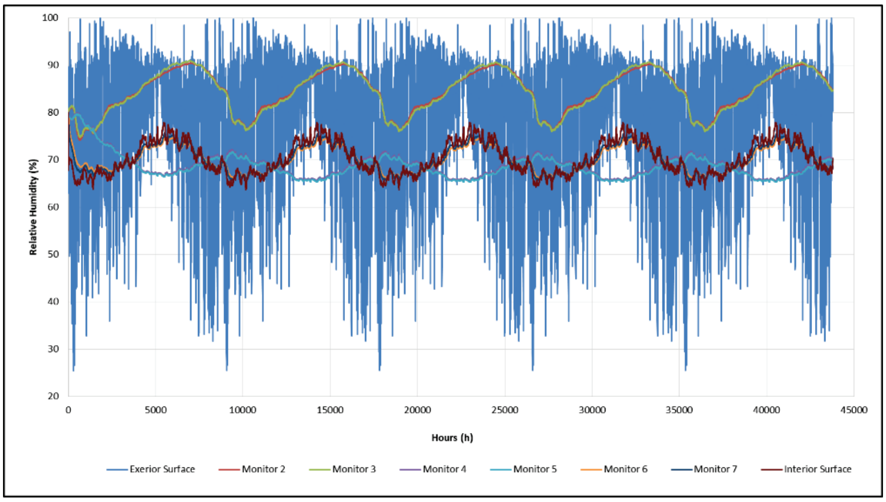


APPENDIX P

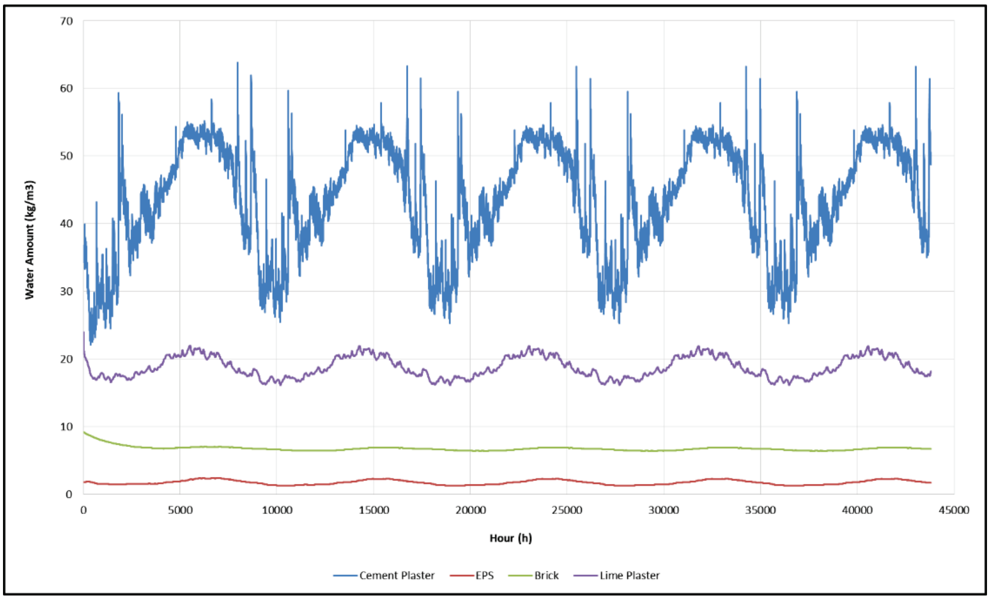
TOTAL WATER CONTENTS IN BRICK WALLS WITH EPS INSULATION



RELATIVE HUMIDITY VALUES AT MONITOR POSITIONS IN BRICK WALL WITH INTERNAL EPS

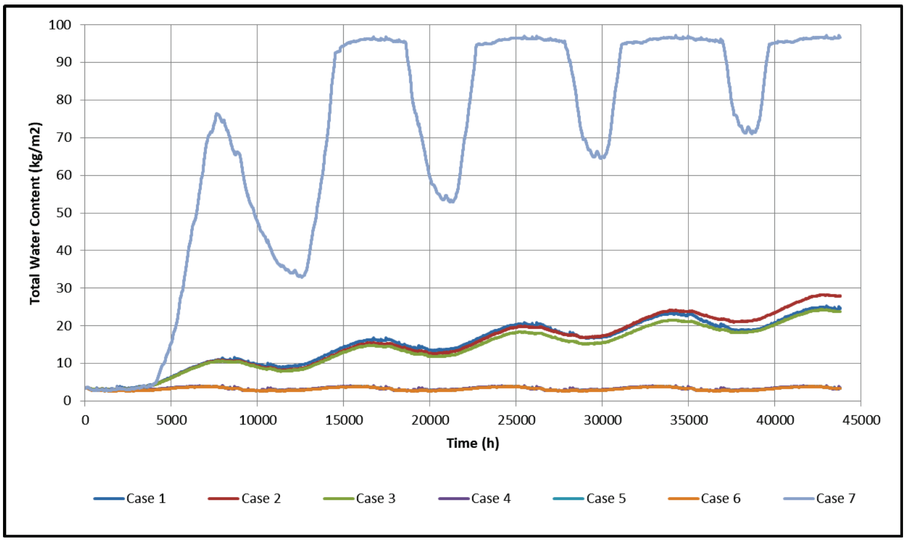


WATER CONTENTS OF INDIVIDUAL MATERIALS IN BRICK WALL WITH INTERNAL EPS

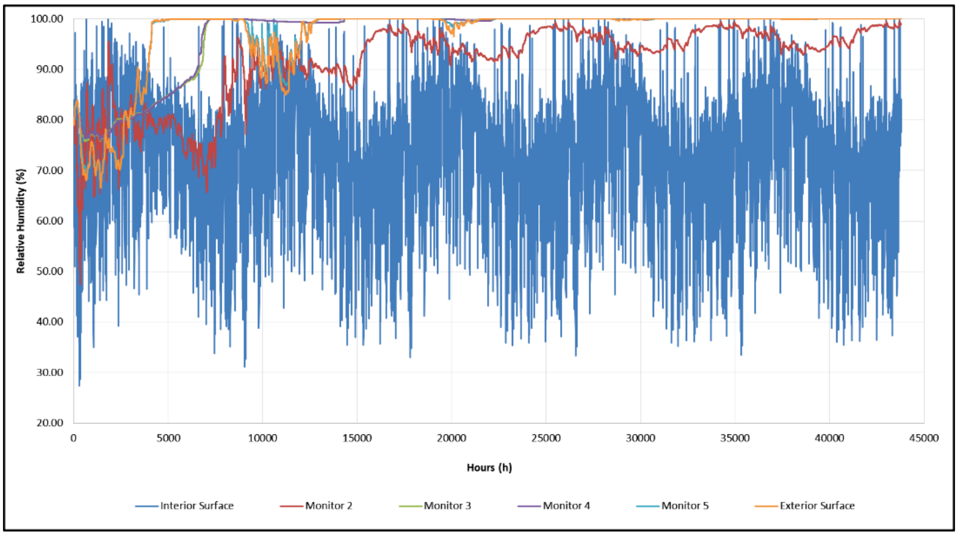


APPENDIX R

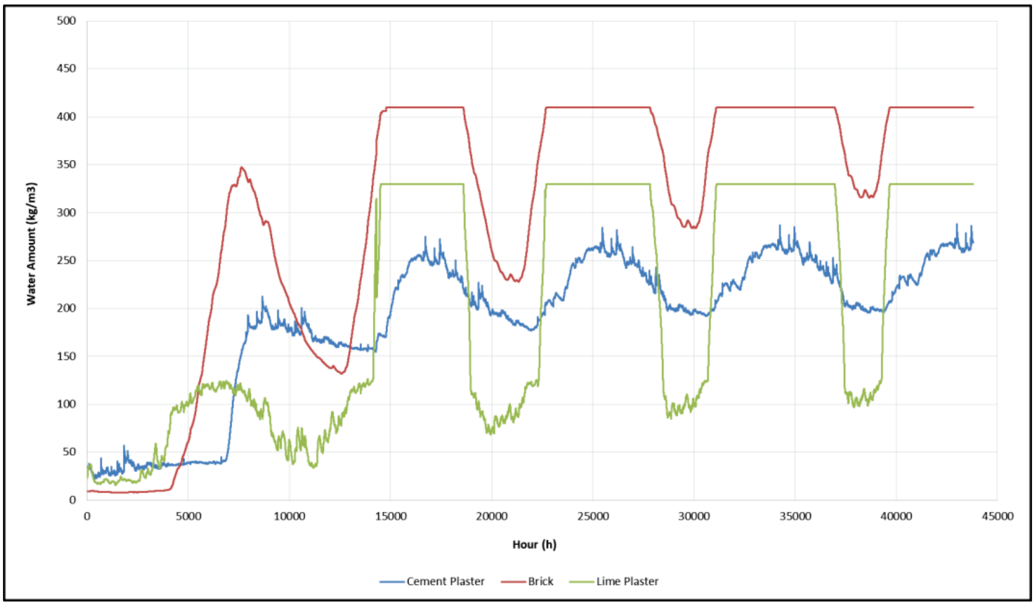
TOTAL WATER CONTENT IN BRICK WALL WITH MW INSULATION



RELATIVE HUMIDITY VALUES AT MONITOR POSITIONS IN BRICK WALL WITHOUT MW

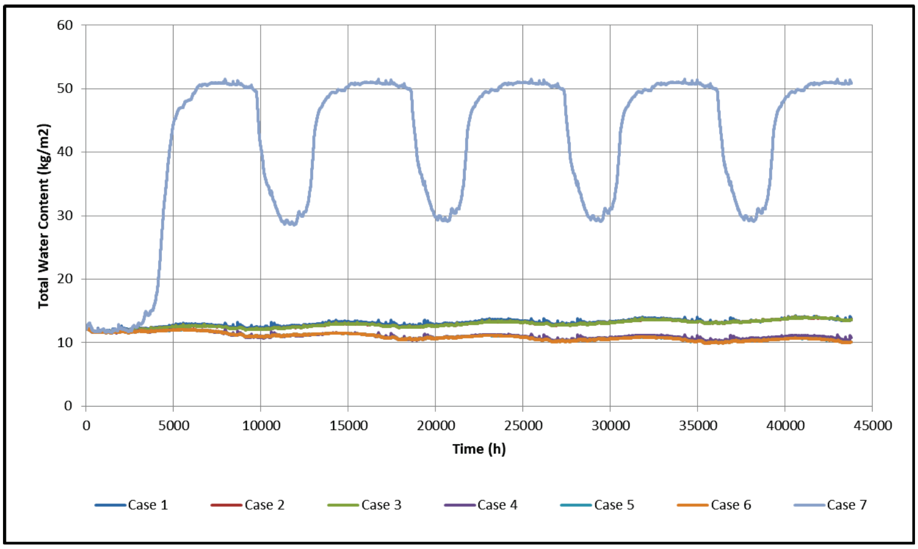


WATER CONTENTS OF INDIVIDUAL MATERIALS IN BRICK WALL WITHOUT MW

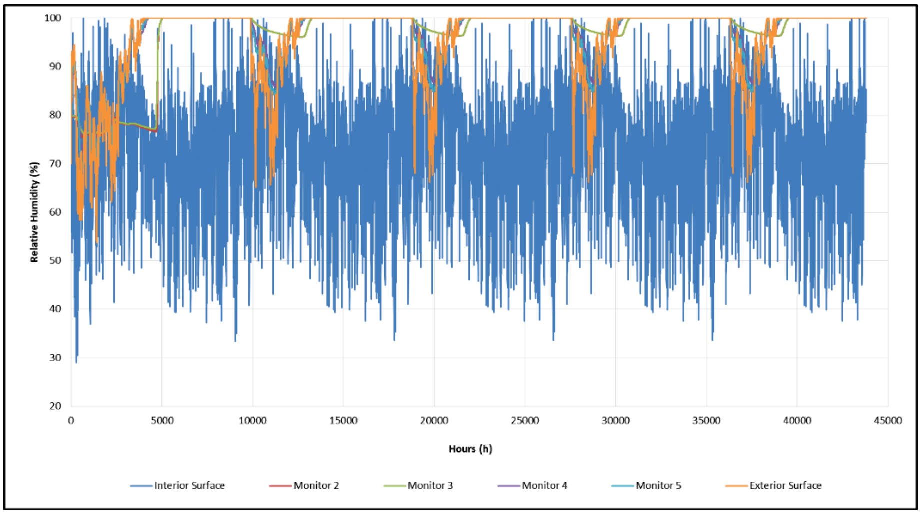


APPENDIX S

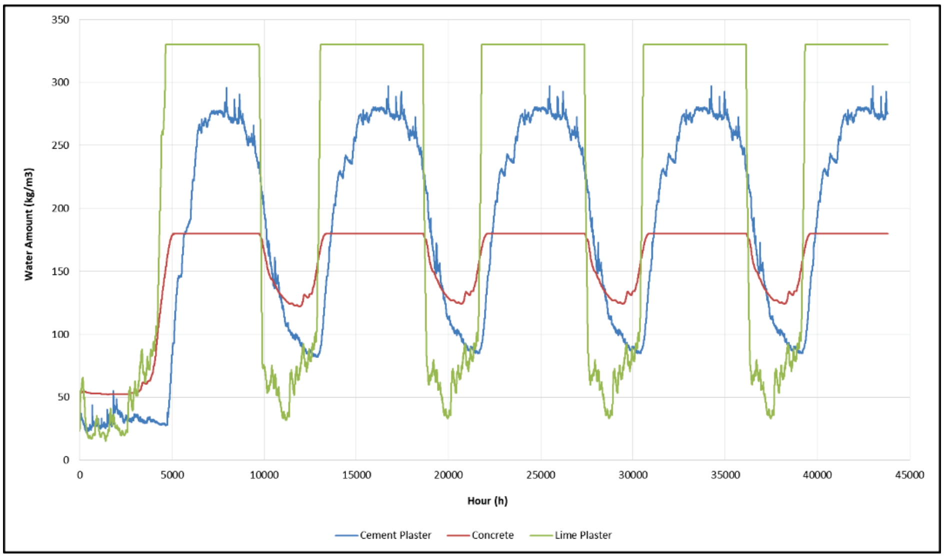
TOTAL WATER CONTENTS IN CONCRETE WALLS WITH XPS INSULATION



RELATIVE HUMIDITY VALUES AT MONITOR POSITIONS IN CONCRETE WALL WITHOUT XPS

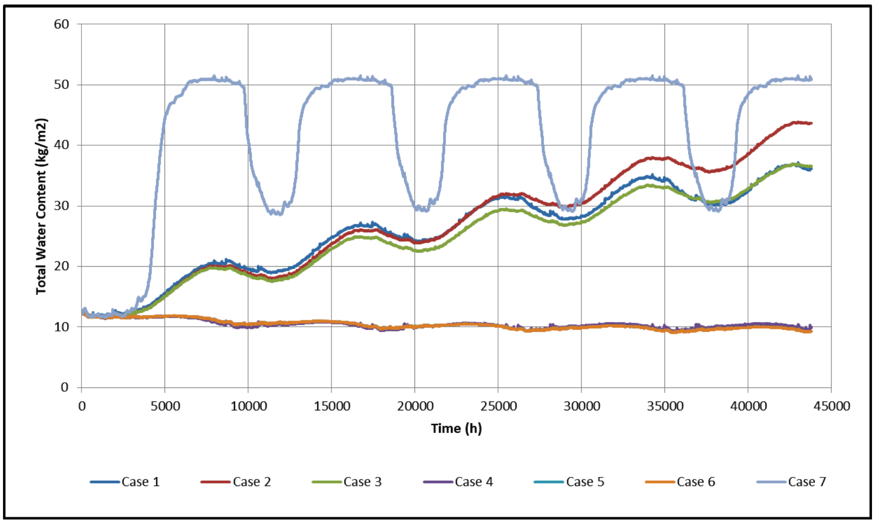


WATER CONTENTS OF INDIVIDUAL MATERIALS IN BRICK WALL WITHOUT XPS

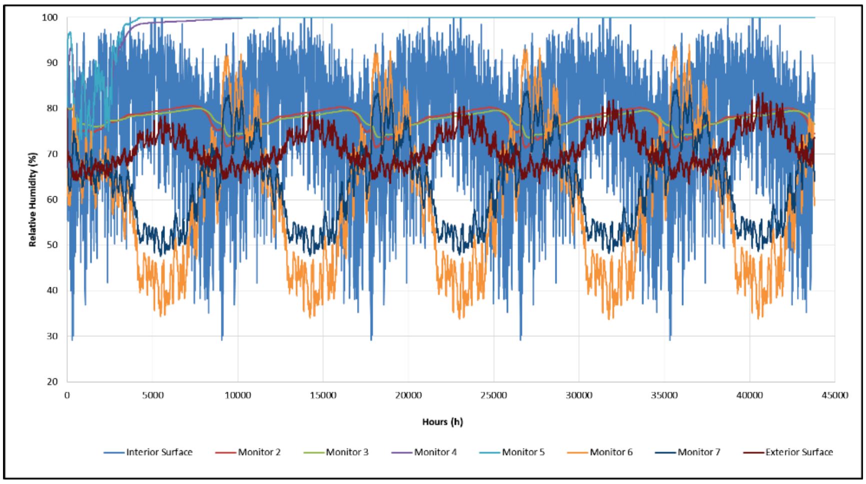


APPENDIX T

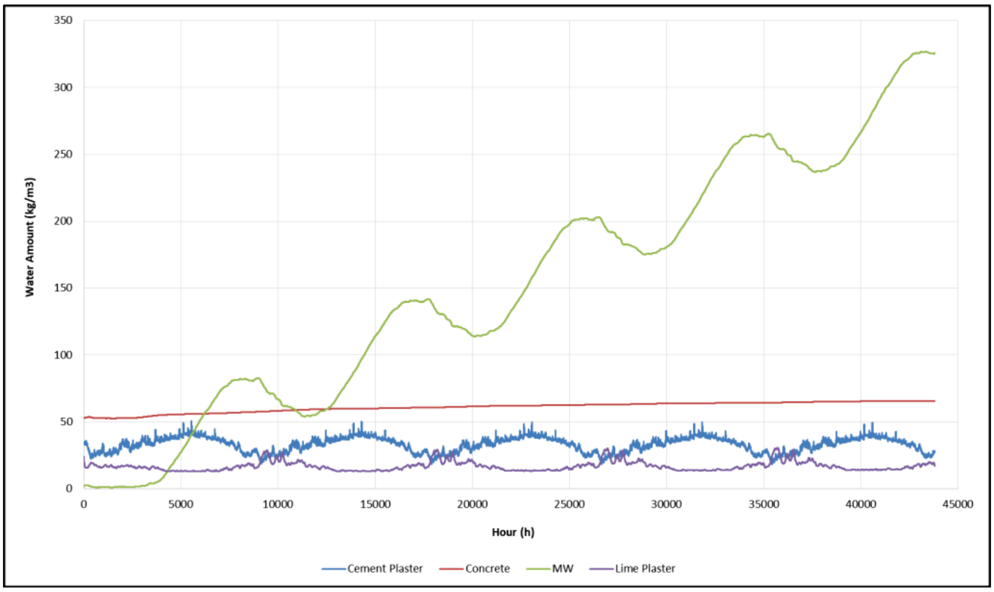
TOTAL WATER CONTENTS IN CONCRETE WALLS WITH MW INSULATION



RELATIVE HUMIDITY VALUES AT MONITOR POSITIONS IN CONCRETE WALL WITH INTERNAL MW

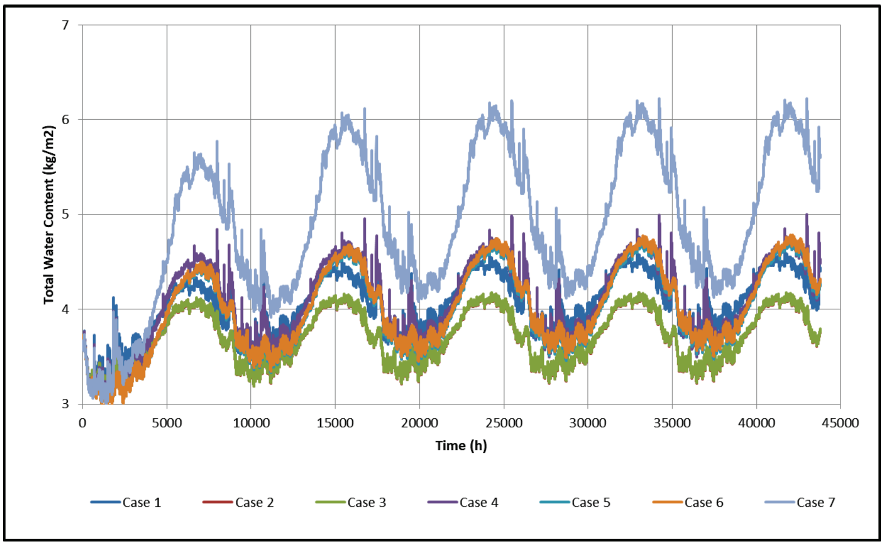


WATER CONTENTS OF INDIVIDUAL MATERIALS IN BRICK WALL WITH INTERNAL XPS

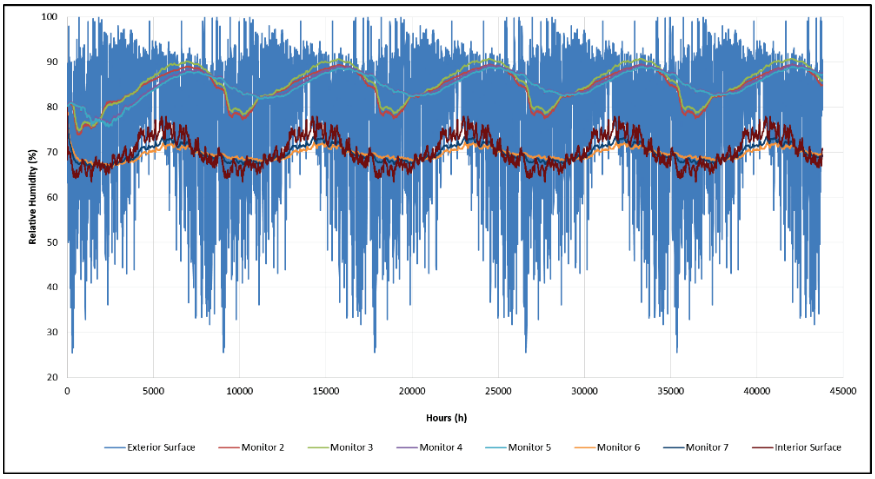


APPENDIX U

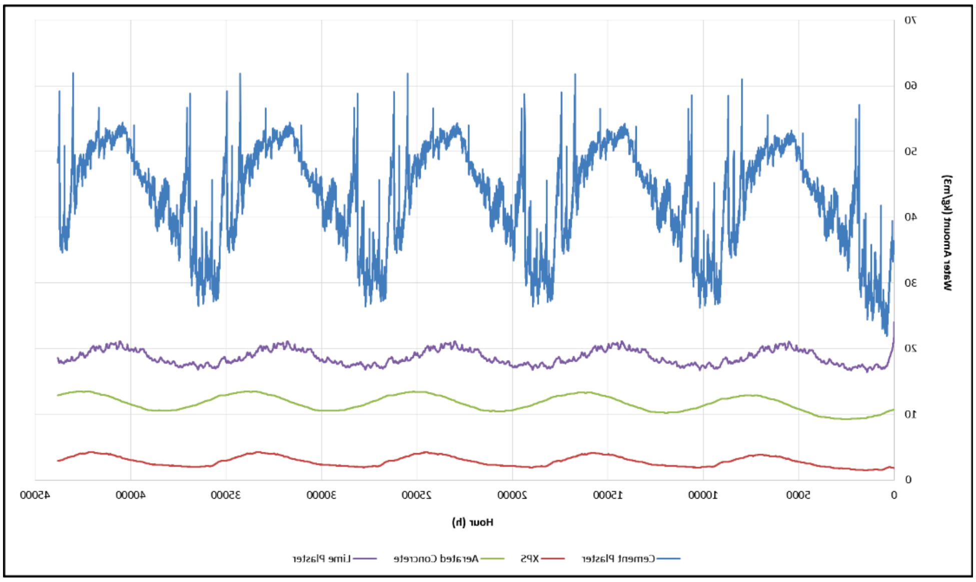
TOTAL WATER CONTENTS IN AERATED CONCRETE WALLS WITH XPS INSULATION



RELATIVE HUMIDITY VALUES AT MONITOR POSITIONS IN AERATED CONCRETE WALL WITH EXTERNAL XPS

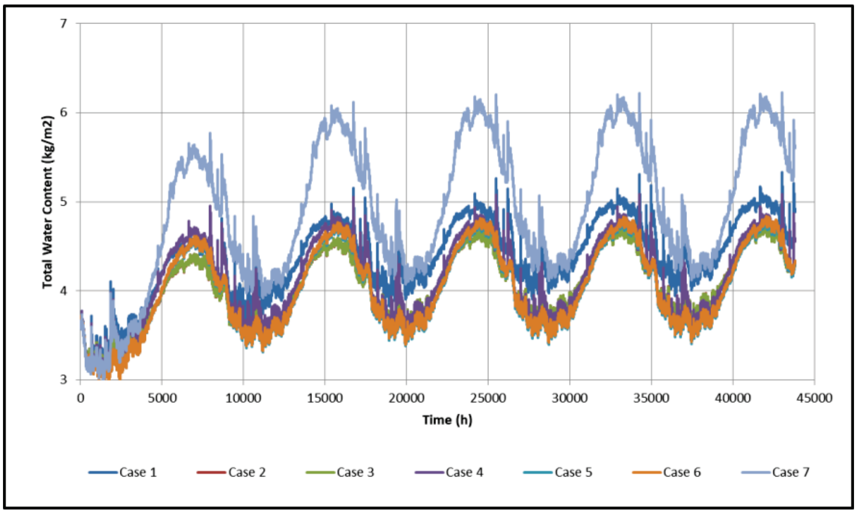


WATER CONTENTS OF INDIVIDUAL MATERIALS IN AERATED CONCRETE WALL WITH EXTERNAL XPS

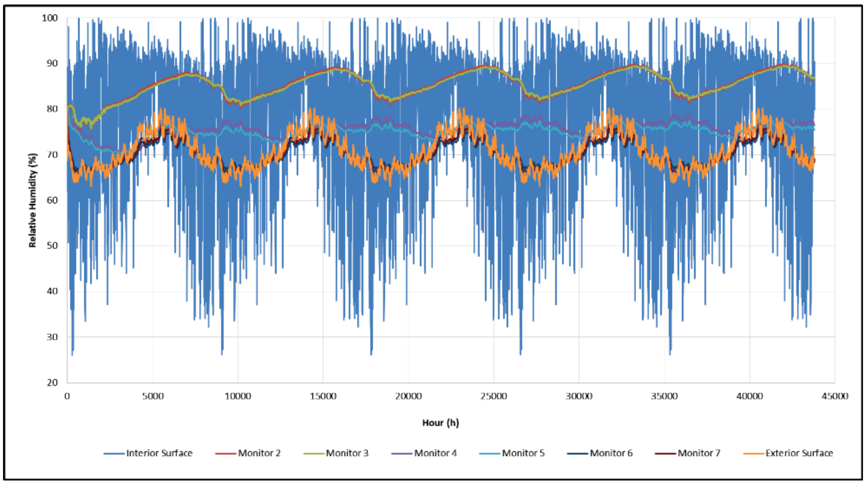


APPENDIX V

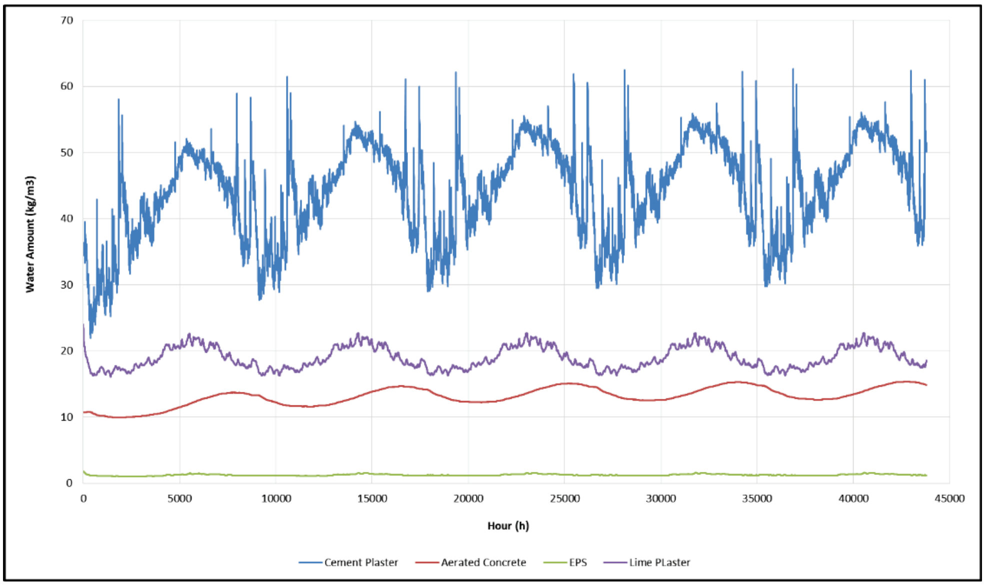
TOTAL WATER CONTENTS IN AERATED CONCRETE WALLS WITH EPS INSULATION



RELATIVE HUMIDITY VALUES AT MONITOR POSITIONS IN AERATED CONCRETE WALL WITH INTERNAL EPS



WATER CONTENTS OF INDIVIDUAL MATERIALS IN AERATED CONCRETE WALL WITH INTERNAL EPS



APPENDIX Y

CODE WRITTEN IN OCTAVE

```
ax=[ 0 , 24 ,624 ,814 , 889];
ay=[ 430 ,419  , 530 , 1961 , 1999];
bx=[ 0 , 889];
by=[ 329 , 1519];

##number1=input("Please enter how many transitions exist in the first function ");
##
##for p=1:number1
##
##fprintf('\n Please enter x value of the %i. point of the first function\n\n',p)
##ax(p)=input('');
##fprintf('\n Please enter y value of the %i. point of the first function\n\n',p)
##ay(p)=input('');
##fprintf('\n %i. point is: (%i,%i)\n',p,ax(p),ay(p))
##


##endfor
##
##number2=input("\n Please enter how many transitions exist in the second function ");
##
##for p=1:number2
##
##fprintf('\n Please enter x value of the %i. point of the second function\n\n',p)
##bx(p)=input('');
##fprintf('\n Please enter y value of the %i. point of the second function\n\n',p)
##by(p)=input('');
##fprintf('\n %i. point is: (%i,%i)\n',p,bx(p),by(p))
##
##endfor
```

```
ds=30;
scale=300;
%input("\n Please enter desired sharpness level of condensate zone demonstration ");

la=length(ay);
lb=length(by);
q=zeros(1,la+lb-2);
index=1;
axx=ax(1):index:ax(length(ax));
lay=zeros(1,length(q));
lby=zeros(1,length(q));

for j=1:(la+lb-2)

  if j<la

      q(j)=(ay(j+1)-ay(j))/((ax(j+1)-ax(j))/index);

      lay(j+1)=length(ay(j):q(j):ay(j+1));

      iyy([1:lay(j+1)])=ay(j):q(j):ay(j+1);

      if j==1

        ayy([1:lay(j+1)])=iyy;

      else

        ayy([(-j+3+sum(lay(1:j))):sum(lay)-j+1])=iyy([2:lay(j+1)]);

      endif

   else
```

```
      m=j-la+1;

      q(j)=(by(m+1)-by(m))/((bx(m+1)-bx(m))/index);

      lby(m+1)=length(by(m):q(j):by(m+1));

      iyy([1:lby(m+1)])=by(m):q(j):by(m+1);

      if m==1

        byy([1:lby(m+1)])=iyy;

      else

        byy([(-m+3+sum(lby(1:m))):sum(lby)-m+1])=iyy([2:lby(m+1)]);

      endif

    endif

endfor

cxx=axx;
cyy=ayy-byy;

[X,Y]=meshgrid(cxx,cyy);

T=zeros(2*max(ay),length(cxx)-1);


n=1;

for i=2:length(cxx)
```

```
  T(:,i-1)=Y'(1,i);

  if T(:,i-1)<0

    T(:,i-1)=T(:,i-1)-scale;

    cxxm(n)=i;

    n=n+1;

  endif

endfor

nocondensation=zeros(256,3);
for i=1:256
  nocondensation(i,1)=i/255-1/255;
  nocondensation(i,3)=1;
end

if n==1
map=nocondensation;
else
map=cool;
end

plot(ax,ay,'-')
hold on
plot(bx,by,'-')
hold on
axis([0 max(ax) 0 max(ay)+by(1)])

imagesc(T)
colormap(map)
```

```
hold on
plot(bx,by,'-',"markersize", ds)
hold on
plot(ax,ay,'-',"markersize", ds)
hold on
plot(bx,by,'.',"markersize", ds)
hold on
plot(ax,ay,'.',"markersize", ds)
hold on
plot(bx,by,'.',"markersize", ds)
hold on
plot(ax,ay,'.',"markersize", ds)
hold on
u=[0,2*max(ay)];

plot([ax(2),ax(2)],u,'k')
hold on
plot([ax(3),ax(3)],u,'k')
hold on
plot([ax(4),ax(4)],u,'k')
hold on

for i=1:4
u(i)=(ax(i)+ax(i+1))/2;
endfor

xticks([u(1) u(2) u(3) u(4)])

xticklabels({'C. P.','Brick','EPS','L. P.'})
```