ITU A|Z • Vol 20 No 2 • July 2023 • 333-345

An analysis on hygrothermal behaviour of traditional timber framed brick infill exterior wall

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Received: November 2022 • Final Acceptance: February 2023

Abstract
The goal of this study is to analyze hygrothermal performance of traditional timber framed brick infill exterior wall in Turkey to investigate the physical conditions of these buildings as an input for conservation/restoration/reconstruction projects. In order to investigate hygrothermal performance of the wall assembly, numerical and experimental studies were adopted. The numerical study was examined by DELPHIN simulation tool and guarded hot box is used for the experimental study. Based on the results of literature review; the system, and layers of external wall of traditional timber framed brick infill houses in Sivrihisar were examined. Then, the wall assembly were designed for case study. The evaluation is based on laboratory measurements that are used for comparison of the numerical modelling by analysis of temperature and U-value. The results indicate that experimental study has crucial role for applicability of numerical modelling for hygrothermal performance evaluation. Notably, material variations create unexpected impacts on the wall layers. The simulated values have good agreements with measured values on the infill parts of the wall assembly. In contrast to that the differences between measured and simulated wooden parts of the wall assembly are needed to be examined. The intersection and interaction points of different materials are required to assess by experimental and numerical methods for further studies in detailed.

Keywords
Brick infill, DELPHIN, Hygrothermal performance, Guarded hot box, Traditional timber framed exterior wall.

doi: 10.58278/0.2023.14

1. Introduction

Hygrothermal performance concentrates on air, moisture, and heat movements through building elements. Hens (2002) states that heat, air, and moisture movement have imp acts on durability and thermal quality. Vapor permeability and thermal resistance are two major factors for building façade performance (Pihelo & Kalamees, 2016). These factors are fundamental considerations for the analysis of hygrothermal performance of a wall. User comfort, durability of material and energy efficiency of buildings are directly related with hygrothermal performance (Gasparin et al., 2019). Trechsel (2001) points out that to supply comfort conditions of users it is necessary to control the relative humidity of both the space and the surface at the recommended limit values. To design a well-performed building envelope of nearly zero energy buildings, hygrothermal design criteria considering material properties are needed to be assessed (Pihelo et al., 2016). A problem about building envelope and/or its hygrothermal performance may be a reason of the undesirable biological structures, building material deterioration and energy usage increasement. Moisture accumulation in the building envelope causes physical, biological, and/or chemical deterioration based on local conditions (Nofal et al., 2001). Chang and Kim (2015) explain that mould growth has serious impacts on buildings and also users' health. Corrosion, biological growth, and freeze-thaw through a wall lead to damages of building and building materials as well in historic buildings (Gutland et al., 2021).

Hygrothermal performance is explained as thermal and moisture properties of heat, air, and moisture movement by building physicists (Kumaran, 2001). Altun (1997) claims that while thermal performance requires minimum heat loss in heating season, minimum heat gain in cooling season, ability to keep the internal surface temperature at the desired level, resistance to thermal deformation, heat storage feature, resistance to high and low temperatures; moisture performance requirements can be listed as no moisture accumulation and no physical, chemical, biological related deterioration throughout the wall. Hygrothermal performance inquires heat flow by radiation, conduction, and transport; vapor flow by vapor diffusion and liquid convection; air flow formed by natural, external, and mechanical forces (Delgado et al., 2013).

Hygrothermal performance analysis methods are main research questions of several studies. Specifically, hygrothermal simulation tools are examined in terms of their time and cost efficiency. Calculation methods are mostly applied methods comparing with laboratory and measurements depending on time and cost efficiency (Kalamees & Vinha, 2003). There are numbers of hygrothermal simulation tools. In the literature most of the studies concentrated on applicability, reliability, and validity of these hygrothermal simulation tools (Pihelo and Kalamees, 2016; Kalamees and Kurnitski, 2010; Kalamees & Vinha 2003; Zarr et al., 1995). Moreover, there are numerous research about hygrothermal simulation tools (Defo et al., 2022; Hejazi et al., 2019; Barreira et al., 2013; Delgado et al., 2013; Kalamees & Vinha, 2003). Besides, several studies cover hygrothermal performance of timber framed walls mostly concentrating on energy efficiency and moisture-related issues (Schjøth Bunkholt et al. 2021; Fu et al. 2020; Cabrera et al 2019; Liu et al. 2018; Martinez, 2017; Pihelo and Kalamees, 2016; Pihelo et al. 2016; Kalamees and Vinha, 2003; Zarr et al. 1995).

Literature review points out that hygrothermal performance of walls are rarely searched in Turkey (Çiçek, 2002; Engin, 2005; Yücel Dalkıran, 2008; Alan, 2010; Kuş et al., 2010; Umaroğulları, 2011; Samancı, 2019; Turgut, 2019). It is observed that many of these studies are comprised contemporary materials and constructions; hygrothermal performances of traditional timber framed houses in Turkey have not been analyzed yet. Beside it is seen that these studies mostly preferred to apply WUFI for hygrothermal modelling instead of DELPHIN. WUFI, as a hygrothermal simulation tool, was developed by Fraunhofer IBP (Institute for Building Physics) in 1995. DELPHIN is a hygrothermal simulation tool, which was developed by the Institute for Building Climatology at Dresden University of Technology (Faculty of Architecture) in 1997. These are the two leading hygrothermal simulation tools in the literature. Both of them are capable for 1D, 2D and 3D modelling by using real weather file. They have their own material library for hygrothermal performance analysis. While DELPHIN creates 2D grid for calculation and considers the gravity, WUFI creates 1D grid for calculation and does not consider the gravity for analysis.

This research focuses on hygrothermal performance analysis of the traditional timber framed brick infill exterior wall in Sivrihisar, Turkey adopting numerical modelling and laboratory study. It is aimed to examine firstly the accuracy of simulation tool results by comparing laboratory study, secondly the applicability of the laboratory and numerical methods of hygrothermal performance analysis for traditional timber framed exterior walls in long term and finally collecting data about the hygrothermal performance of the wall assembly as inputs for the improvement of approaches and intervention strategies in conservation and preservation research for energy efficiency of these buildings.

2. Materials and methodology

The method of this research is conducted on three main parts: (1) a comprehensive literature review, (2) experimental study and (3) numerical study.

The first phase of the research is started with a comprehensive literature review. The purpose of this phase is to create theoretical data about the hygrothermal performance analysis and the wall specimen design. Literature review generates the theoretical knowledge about the hygrothermal performance analysis and inputs about wall assembly design criteria.

Based on the results of literature review; the system, and layers of external wall of traditional timber framed brick infill houses in Sivrihisar were examined. The ratio of wooden and infill materials of the selected façade examples in the literature are calculated to design the wall assembly as case study.

Numerical method is the most preferred hygrothermal performance analysis methods considering cost and time efficiency. However, numerical method data requires comparison with experimental method. Most of the research adopt numerical method with the experimental method by comparing data to prove the accuracy and reliability of the results. Together with the numerical analysis data, experimental method application is necessary to validate the numerical analysis results (Asdrubali & Baldinelli, 2011). Consequently, this study adopts both numerical and experimental methods for the hygrothermal performance assessment of the wall assembly.

DELPHIN was applied for the numerical analysis of the wall assembly. It is a user-friendly simulation tool that has capability of examination of hygrothermal performance, moisture-based problem, insulation proposals, thermal performance improvement etc. Furthermore, it makes analysis about the heat, moisture, air, and salt transport in building materials. Additionally, DELPHIN is one of the mostly used hygrothermal simulation tools. A study about hygrothermal simulation tools, which includes searching on Google Scholar, Web of Science, Scopus and ScienceDirect with the keyword "(program name + hygrothermal)", states that DELPHIN is the secondly most applied hygrothermal simulation tool (Yıldız, 2021).

The experimental study has two phases: (1) material properties analysis and (2) guarded hot box analysis. Material properties analysis were conducted on Istanbul Technical University Faculty of Architecture Construction Materials Lab. Thermal conductivities of brick and timber specimens were measured by Düzce Üniversitesi Bilimsel ve Teknolojik Araştırmalar Uygulama ve Araştırma Merkezi. Guarded hot box analysis was realized in the Turkish Standards Institution Construction Materials Fire and Acoustic Laboratory. In the hot box setup, the sample to be tested is placed in the designated area between the hot and cold chambers with known ambient temperatures, and it is carried out while powering the part on the hot chamber side at steady-state air and surface temperatures. According to these measurements, the properties of the test sample about heat conduction can be calculated. Heat exchange on the surfaces of the test sample includes transport and radiation components (Turkish Standards Institution, 2002).

The research steps are visualized on Figure 1.

3. Description of wall assembly

Within the scope of the experimental study, the major phase is to design wall specimen. To investig ate the system and the layers of the traditional timber framed brick infill exterior wall in Sivrihisar, a comprehensive literature review was conducted. Specific exterior wall examples are selected to calculate the system configuration and the ratio of wooden and infill material. Afterwards, depending on this data the wall specimen is designed as 150 cm x 150 cm.

The dissertations in the preservation and restoration area were primarily examined in the analysis of the traditional timber framed brick infill exterior wall in Sivrihisar, Eskişehir. Due to the limited data in the other sources, the two resources were applied to analyze ratio of wooden and infill areas for calculation. These resources supplied required data for wall layers and drawings of façades. These drawings were re-drawn to determine wooden elements sizes and façade design.

Demberel (2012) worked on a restoration proposal in the thesis titled "The Proposal for The Restoration of Sivrihisar İbrahim Bulgurcu House". The three different parts from southeast, southwest, and northwest façades of the building, which was built with timber framed brick infill technique, were selected to make calculation for wall specimen design. The ratio of wooden area was approximately determined as 39.46% and the infill area was 60.54% on the southeast, the wooden area on the southwest was 50.99% and the infill area was 49.01%, the wooden area was 28.57% and the infill area was 71.43% on the northwest façade. While outer surfaces of the façades are not plastered, the inner surfaces are plastered (Demberel, 2012).

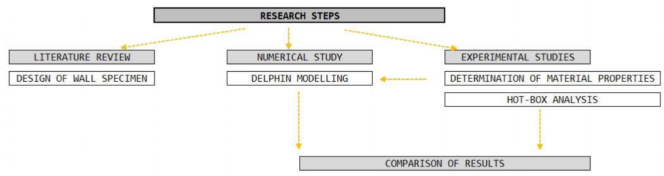

Figure 1. *The research steps.*

Figure 2. *İbrahim Bulgurcu House, Southeast façade (Demberel, 2012).*

Figure 3. *Zaimoğlu Konağı, Southeast façade (Uslu, 2003).*

Uslu (2003) studied about the restoration project of a mansion within the scope of the thesis titled "The Restoration Project of Zaimoğlu Konağı in Sivrihisar". A selected part from southeast façade of the building, which was built with timber framed brick infill technique, was examined. The wood area ratio was calculated as 40.89% and the infill area as 59.11%. While the outer surface of the façades are not plastered, the inner surface was finished with approximately 1 cm of lime

Table 1. *Data about the examined façade samples.*

	Source	Total Area of Façade cm²	Total Area of Façade Without Opening cm²	Infill Area cm²	Wooden Area cm²	Infill Area %	Wooden Area %
Examined Samples for Sivrihisar, Eskişehir	Demberel, 2012 (southeast)	114688.56	94909.04	57455.2	37453.84	60.54	39.46
	Demberel, 2012 (southwest)	145500	114720	56222.99	58497.01	49.01	50.99
	Demberel, 2012 (northwest)	84000	84000	60000	24000	71.43	28.57
	Uslu, 2003 (southeast)	270000	227388.91	134399.96	92988.95	59.11	40.89
AVERAGE						**60.02**	**39.98**

Table 2. *Data about the wall assembly.*

	Total Area of Façade cm²	Total Area of Façade Without Opening cm²	Infill Area cm²	Wooden Area cm²	Infill Area %	Wooden Area %
Wall Assembly	22.500	22.500	13224.72	9275.28	58.78	41.22

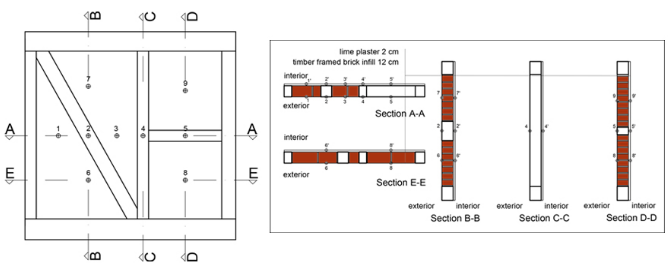

Figure 4. *The wall assembly drawings.*

plaster application on nearly 3 cm of mud plaster (Uslu, 2003).

The studied examples are explained above. The data showing results of the approximate ratios of wooden area and infill area of the selected examples are expressed in Table 1.

The results of these analysis expressing in Table1 are applied as input for wall assembly design. Even the directions of the façades are not same, these data are aimed to use to generalize the wall type for specimen design. The ratio of wooden and infill area of the wall assembly are presented on Table 2. The materials and details were determined based on the most constructed timber framed brick infill exterior wall types in Turkey in size of 150 cm x 150 cm. The layers of the wall specimen from outside to inside; timber frame brick infill 12 cm and lime plaster 2 cm.

The measurements of the wall assembly were provided with 18 thermocouples (9 thermocouples are located in cold side and 9 thermocouples are symmetrically located in warm side) placed at critical points to evaluate the intersections and interactions of different materials both vertically and horizontally. The timber frame of the wall assembly and the location of the 9 thermocouples at cold side are showed by numbers in Figure 4 on the left; layers, the sections and measurement points are placed Figure 4 on the left.

4. Experimental studies

The experimental studies of this research are based on two parts: (1) material properties analysis and (2) guarded hot box analysis.

4.1. Material properties analysis

Material properties play significant role in hygrothermal performance simulations. Hygrothermal simulation modelling influences by geometry of enclosure, boundary conditions and material properties (Delgado et al., 2013). Straube and Burnett (2001) state that outputs of hygrothermal simulation are depended on quality and availability of information, material properties, dimension (1D, 2D, 3D), time (steady-state conditions, dynamic regime conditions), climate file, construction quality. In that sense, the material properties are examined to generate accurate data for simulation phase of this study.

The laboratory analysis about bulk density, water uptake coefficient, open porosity, vapor diffusion resistance factor (μ value) and hygroscopic sorption (RH= 80%) values of the materials (brick and timber) were realized. The tested materials were randomly selected. Brick materials were purchased from a brand that makes production in Eskişehir. Timber materials were purchased from a timber company in İstanbul.

Even hygroscopic sorption values (RH= 80%) of the materials were found by the analysis, DELPHIN does not give permission to change these values on the library and they were kept as it is in DELPHIN. Therefore, the selected materials are determined depending on the closer hygroscopic sorption value (RH= 80%) found by the material properties analysis. After finding the material properties by the laboratory analysis, the similar materials of DEL-

PHIN library are edited according to these values. Other material properties seen on DELPHIN library screen were kept as they are defined.

4.1.1. Bulk density analysis

TS EN 1936 standard was applied to determine the bulk density values of the samples. For the determination of the bulk density value, the samples were dried in oven at 100°C until they reached a constant mass, and then cooled in a desiccator until they reached room temperature. The dry mass of the samples was weighed and their dimensions were measured. The bulk density of the samples is calculated with the formula below.

$$\rho_b = \frac{m_d}{a_d.b_d.l_d} = \frac{m_d}{V_d}$$

ρ_b: Bulk density of the sample (kg/m^3),
a_d, b_d, l_d: Dimensions of the dried sample (m),
m_d: Mass of the dried sample (kg),
V_d: Volume of the dried sample (m^3).

4.1.2. Water uptake coefficient analysis

TS EN 1925 standard was applied to determine the water u ptake coefficient values of the samples. For the determination of the bulk density value, the samples were dried in oven at 100°C until they reached a constant mass, and then cooled in a desiccator until they reached room temperature. The dry mass of the samples was weighed and their dimensions were measured. The samples, which were left in the room condition for one day, were weighed again. At the bottom of a container, a stand was put for the placement of the samples. Then the container was filled with water up to a height of (3 ± 1) mm and the chronometer was started. Before each weighing process, drops of water on the surface of the samples were removed for a healthy measurement. After weighing, the samples were quickly returned to the container and the same procedures were repeated at the specified time. The water uptake coefficient values of the samples are calculated with the formula below.

$$N = \frac{m_i - m_d}{A.\sqrt{t_i}}$$

N : Water uptake coefficient of the sample (kg/m^{2}s^{½}),
m_d : Mass of the dried sample (kg),
m_i : The mass of the sample that absorbed water (kg),
A : Area of surface immersed in water (m^2),
t_i : The times during which successive masses were measured (s).

4.1.3. Open porosity analysis

TS EN 1936 standard was applied to determine the open porosity values of the samples. For the determination of the bulk density value, the samples were dried in oven at 100°C until they reached a constant mass, and then cooled in a desiccator until they reached room temperature. The dry mass of the samples was weighed and their dimensions were measured. The samples, which were left in the room condition for one day, were weighed again. Afterwards, the samples were placed in the container where they were completely covered with water. And the chronometer was started. At the end of 24 hours, the saturated mass (ms) and the mass in water (mh) of the samples were recorded by weighing. The open porosity values of the samples are calculated with the formula below.

$$p_o = \frac{m_s - m_d}{m_s - m_h}$$

p_o : Open porosity of the sample (m^3/m^3),
m_d : Mass of the dried sample (m^3),
m_s : Saturated mass of the sample (m^3),
m_h : Mass in water of the sample (m^3).

The unit of open porosity is calculated as % value, but since this value is requested as m3/m3 in DELPHIN software, calculations were made by adjusting the formula accordingly. The founded value was not multiplied by 100 to have the result as m3/m3.

4.1.4. Vapor diffusion resistance factor (μ value) analysis

TS EN 12086 and TS EN ISO 12572 standards were applied to calculated water vapor diffusion resistance factor of the samples. Water vapor permeability test was realized out according to the dry cup method. CaCl2 was used as a desiccant material in the containers. The desiccator conditions used for the experiment were around 20-23°C and 95-100% relative humidity. During the experiment, the samples were weighed periodically. The water vapor diffusion resistance factor values of the samples are calculated with the formula below.

$$\mu = \frac{\delta_a}{\delta}$$

μ : Water vapor diffusion resistance factor (-),
δ_a : Water vapor permeability of air (mg/(mhPa))
δ: Water vapor permeability (mg/(mhPa)).

4.1.5. Hygroscopic sorption (RH= 80%) value analysis

TS EN ISO 12570 and TS EN ISO 12571 standards were applied for this test. The standards describe the drawing of the hygroscopic water absorption curve of building materials and products considering different relative humidity values. DELPHIN software requires the hygroscopic sorption value at 80% relative humidity. However, since there is no test condition defined for this relative humidity condition, 75% and 85% relative humidity conditions specified in the standard were provided to obtain this value, and the hygroscopic sorption value of the materials at 80% relative humidity was found by taking the average of these values.

Appropriate saturated aqueous solutions were created as described in the standard to provide the required relative humidity in the desiccator. Two different solutions were prepared separately to have two different relative humidity values in the desiccators. NACI was used to create 75% relative humidity conditions and KCl was used to create 85% relative humidity conditions.

3 samples for each material, which are prepared as 5x5x5 cm and not less than 10 g, were dried in oven at 100°C until they reached a constant mass, and then cooled in a desiccator until they reached room temperature. Weighing was carried out periodically.

The moisture content by volume, ψ, of the samples are calculated with the formula below.

$$u = \frac{(m - m_d)}{m_d}$$

$$\psi = u \frac{\rho_b}{\rho_w}$$

u: Moisture content by mass (kg/kg),
m: Mass of the sample (m^3),
m_d: Mass of the dried sample (m^3)
ψ: Moisture content by volume (m^3/m^3),
ρ_b: Bulk density of the sample (kg/m^3)
ρ_w: Density of water = 997,6 (kg/m^3).

4.2. Guarded hot box analysis

The wall assembly was constructed by 150 cm x150 cm (h x b) in the Turkish Standards Institution Construction Materials Fire and Acoustic Laboratory. The wall assembly was waited to get dry naturally. Then the wall assembly was put in drying oven for 7 days till its weight got stabilized. Afterwards, the wall assembly was kept under the room conditions for 1 day. Following, thermocouples were installed on the wall as shown in Figure 4 and the wall assembly was installed to guarded hot box between two climatic chambers. Figure 5 presents the experimental study in the laboratory.

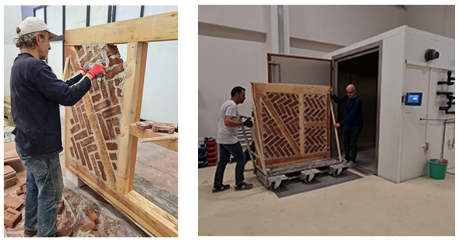

Figure 5. Photos presenting construction and drying oven process of experimental study in Turkish Standards Institution Construction Materials Fire and Acoustic Laboratory.

The warm climatic chamber was arranged as Twarm: 20°C, and the cold climatic chamber was arranged as Tcold: 0°C. The climatic chambers were automatically controlled to keep constant temperature value. The relative humidity of the chambers was set as 50%. The duration of the test was 143 hours.

5. Numerical modelling: DELPHIN hygrothermal simulation tool

The outputs of the laboratory measurements are applied for the validation of DELPHIN simulation tool for the hygrothermal performance analysis of the wall assembly. The measurement points for simulation are determined as same with hot box apparatus measurement points shown in Figure 3.

For simulation process in DELPHIN, a dialog for automatic discretization should be created. In this dialog, the construction is discretized as minimum element size 1 mm, maximum element size 50 mm and stretch factor 1.6. The dialog generates a grid for calculation.

5.1. Boundary conditions

Boundary conditions were arranged as same with guarded hot box analysis for comparison of the data. DELPHIN simulations were realized under the steady state conditions to compare guarded hot box analysis with DELPHIN hygrothermal modelling. Therefore, boundary conditions were determined same as with guarded hot box analysis conditions which is advised in TS EN ISO 8990. Indoor environment was arranged as T_{indoor}: 20°C, RH_{indoor}: 50%, outdoor environment was arranged as $T_{outdoor}$: 0°C, $RH_{outdoor}$: 50%. The initial temperature was set at 20 ^{0}C and the relative humidity at 50%. The orientation of the wall assembly was arranged to 0 Deg for North and the inclination to 0 Deg for Section A-A, 90 Deg for Section B-B and Section C-C. The effect of rain and solar radiation on the walls in the south and west directions cause complicated effects for the comparison studies (Borderon et al., 2016). Because of the elimination of these effects, it is supposed that the wall assembly is facing northwards. The guarded hot box measurements were stabilized after 143 hours. Therefore, the duration of the simulation was arranged as 143 hours.

The hygrothermal performances of the wall assembly is evaluated by analysis of temperature, relative humidity, and U-value.

5.2. Material properties

Assigning materials for hygrothermal simulations has critical impacts on illustrating the real conditions. Therefore, except the lime plaster properties of used materials for wall assembly were analyzed in the laboratory and defined as presented in the headline of "4.1. Material Properties Analysis". Thereafter defining the sections of wall assembly by sizing and layers, materials were assigned to the models by editing the similar materials of DELPHIN library with determined material properties. The material properties of the assigned materials in DELPHIN is presented in the Table 3.

For lime plaster DELPHIN library was used to assign material properties. The assigned material number for lime plaster is 148 named as lime plaster (historical).

Table 3. *Material properties.*

Layer of wall specimen	Thickness (cm)	Edited material ID no in DELPHIN library	Assigned material properties determined by laboratory analysis				
			Bulk density (kg/m^3)	Water uptake coefficient (kg/(m^2·s$^{0.5}$))	Open porosity (m^3/m^3)	μ value (-)	Thermal conductivity (W/mK)
Timber	12	714	800.1306	0.0200	0.0376	164.6604	0.1823
Brick	12	686	1655.5502	2.9999	0.2956	16.5792	Cannot be measured. DELPHIN library value was assigned.

Table 4. *The summary of comparison temperature value of laboratory test and numerical modelling.*

Thermocouple no	Measured – Temperature (°C) Warm side	Simulated – Temperature (°C) Warm side	Differences	Differences (%)	Measured – Temperature (°C) Cold side	Simulated – Temperature (°C) Cold side	Differences	Differences (%)
1	19.86	13.10*	-6.76	**-34.04**	0.65	3.30*	2.65	**407.69**
2	16.06	15.42*	-0.64	-3.99	1.75	1.46*	-0.29	-16.57
		16.16**	0.10	0.62		1.43**	-0.32	-18.29
3	14.71	13.14*	-1.57	-10.67	2.93	3.3*	0.37	12.63
4	20.51	15.63*	-4.88	**-23.79**	2.25	1.56*	-0.69	**-30.67**
		16.76***	-3.75	-18.28		1.52***	-0.73	**-32.44**
5	17.26	16.76*	-0.5	-2.90	1.23	1.51*	0.28	**22.76**
		14.83****	-2.43	-14.08		1.587****	0.35	**28.46**
6	15.51	12.98**	-2.53	-16.31	3.33	3.30**	-0.03	-0.90
		13.04*****	-2.47	-15.93		3.30*****	-0.03	-0.90
7	14.97	12.98**	-1.99	-13.29	3.21	3.3**	0.09	2.80
8	15.07	12.95****	-2.12	-14.07	3.90	3.29****	-0.61	-15.64
		12.96*****	-2.11	-14.00		3.29*****	-0.61	-15.64
9	14.97	12.95****	-2.02	-13.49	1.98	3.29****	1.31	**66.16**

* The value refers to simulation of Section A-A.
** The value refers to simulation of Section B-B.
*** The value refers to simulation of Section C-C.
****The value refers to simulation of Section D-D.
***** The value refers to simulation of Section E-E.

6. Results and discussions

The evaluation includes the comparison of guarded hot box analysis and DELPHIN hygrothermal modelling. The temperature and U-value of these analysis are compared for validation of the data. U value is calculated according to the national standard of thermal insulation requirements for buildings in Turkey, TS825. The recommended U value in the standard is 0.48 W/m2K for the exterior wall in Eskişehir.

Firstly, temperature values of guarded hot box analysis and DELPHIN numerical modelling are examined. Total

Table 5. *The output of U value of the guarded hot box analysis and DELPHIN hygrothermal modelling comparison.*

	Thermal conductivity (W/mK)	U-value (W/m²K)
Wall assembly (guarded hot box)	-	1.790
Section A-A	0.210	1.200
Section B-B	0.210	1.200
Section C-C	0.210	1.200
Section D-D	0.210	1.200
Section E-E	0.210	1.200
	U-value differences between measured-simulated	-0.590
	Differences between measured-simulated (%)	-33.23

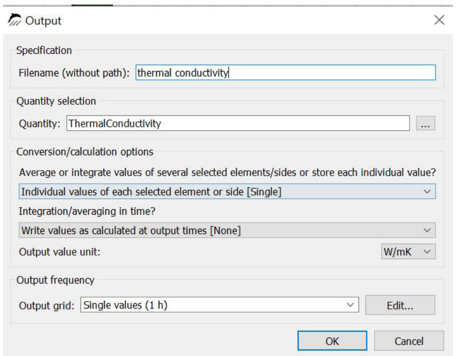

Figure 6. *DELPHIN generated thermal conductivity values as outputs of simulations.*

of 18 measurements points locating symmetrically inside and outside of the wall assembly supplies data. Figure 2 presents the detailed information about the measurement points and sections of the wall assembly. The measured and simulated values of temperature at the end of 143 hours are expressed in Table 4.

Due to the measured data of number 1 cold side is differed too much from the other measured data of cold side, this value is not regarded for data analysis to prevent misinterpretation. Except from 1 (warm side), 4 in Section A-A (warm side), 4 (cold side), 5 (cold side) and 9 (cold side), the difference between measured and simulated values is mostly around 15%.

In order to examine the data accurately, the results are evaluated by material differences and section points. Therefore, the measurement points are classified according to their materials and intersections. The first group is listed as 1,3, 6, 7, 8 and 9 measurement points which are located infill parts. The compared data of these points show that except form measurement point 1 (warm side) and 9 (cold side), the differences between measured and simulated values are approximately 15%. The differences in measurement point 1 (warm side) -34.04%. The differences in measurement point 9 (cold side) 66.16%. On the other hand, the differences decrease in measurement point 6 and 7 on cold side as around 1-2%.

The second group is 2 and 5 locating wooden elements between infill parts. On the warm side the differences between measured and simulated values are closed to 2%. However, in measurement point 5 (cold side) the difference is 22.76%. On the cold side, the differences between measured and simulated values of 2 is between -16.57%.

The third group includes measurement point number 4 locating on the wooden stud. Except from Section C-C (warm side), the differences between measured and simulated values of 4 are between -20% and -30%. On warm side the differences between measured and simulated values of 4 (Section C-C) is -18.28%.

Following, U-values of the guarded hot box analysis and DELPHIN hygrothermal modelling are expressed in Table 5.

The U-value of the wall was measured as 1.790 W/m2K by the guarded hot box apparatus. DELPHIN generated thermal conductivity values as outputs of simulations (Figure 6).

Afterwards, U-value was calculated as 1.200 W/m2K according to the outputs. The difference between measured and simulated U values is -33.23%.

The first part of this study presents the evaluation laboratory test and numerical modelling comparison in terms of temperature and U values. It is clear that the materials intersections and interactions varying plays significant role to examine the results. The data show that the measured and simulated values are affected directly the wooden parts. The differences of the measured and simulated values increased on these measurement points (4 and 5). In contrast to that measurement point 2 does not behave same with these two points. Here, it is assumed that the distances between wooden studs may play role for the variation. For the measurement points on infill part, it is observed that the differences between measured and simulated values are mostly closed to 10-15%. Regarding these measurement points, it may be accepted that there is a good agreement with the measured values and simulated values. Material properties of brick and its smooth surface may have effects on the data. In contradistinction to that circumstance, the differences between measured and simulated values of measurement points 1 (warm side) and 9 (cold side) are not closed to each other. The reason may depend on the gaps between infill and lime plaster. Because in these parts, a smooth and voidless surface cannot formed perfectly. Therefore, these voids may have impacts as an air circulation paths throughout the wall. In addition, workmanship has a critical role. Even the wall assembly constructed attentively, it is impossible to construct it well as assumed in the simulation. Furthermore, the differences between measured and simulated values decrease on the warm side of the wall assembly. It is assumed that lime plastered finishing layer of the warm side may act as a factor to be a smooth and voidless surface.

Within the scope of this study, material properties were assigned for the simulations by editing determined values of the selected materials in DELPHIN library. The simulation data is applied to compare guarded hot box analysis and numerical modelling. In that case, the material properties play crucial roles as being same with the constructed wall specimen and the simulated wall assembly for certain data. It gives opportunity to examine the results regarding accuracy and validation. It creates a data for analysis of hygrothermal performance of the wall assembly with same inputs by two different method application. For the further studies, this consideration is required to be applied for different types of wall assemblies to clarify the impacts of material variations, interactions, and intersections of different materials.

The results of both guarded hot box analysis and DELPHIN model show that U value of the wall assembly cannot achieved the recommended value in TS825. Considering this result, it is critical to improve the U value of the wall assembly by conserving its historical, architectural, cultural, and social values. Because of it requires a comprehensive study, insulation proposals for the improvement are not discussed in this research. Merely, it may be important to specify the beneficials of natural based insulation materials for these types of improvements. Besides, to preserve the originality and uniqueness of the outer surface the wall, it is crucial to consider insulation material application to the inside of the wall. However, moisture-based problems in the long-term requires to be analyzed in detail.

7. Conclusion

The aim of this research is to investigate hygrothermal performance of traditional timber framed brick infill exterior wall in Turkey by experimental and numerical methods. This research contributes to make discussions about the hygrothermal performances of traditional timber framed brick infill exterior walls in Turkey and also applicability of simulation tools with experimental methods. The expected outcome of this research is to generate a significant source to be applied for the conservation/restoration/reconstruction projects of traditional timber framed houses as a tool.

The results shows that experimental study has a critical to accuracy of numerical modelling for hygrothermal performance evaluation. Particularly, material variations create unexpected impacts on the wall layers. The intersection and interaction points of different materials are needed to be deeply analyzed by experimental and numerical methods.

The simulated values have good agreements with measured values on the infill parts of the wall assembly. Contrary, the differences between measured and simulated wooden parts of the wall assembly are subjected to discuss.

Application of material properties both experimental and numerical studies supply a valuable data are for further studies to both validation of numerical modelling and also long-term performance analysis. However, different types of wall assemblies with numbers of examples are needed to be examined.

The scope of this research does not include long term hygrothermal performance of the wall assembly with climatic data. However, the study is subjected to investigate the hygrothermal performance of the wall assembly with climatic data in terms of temperature, relative humidity, and U Value outputs. Especially, with this work it is expected to create a comprehensive data for moisture-based problem analysis. Additionally, field measurements of specific buildings may be applied for comparison of experimental and numerical studies.

Acknowlegement
This work was supported by Scientific Research Projects Department of Istanbul Technical University. Project Number: 42955.

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