Measurement, Prediction And Simulation Methods of Moisture Content In Buildings

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ABSTRACT

This thesis represented some information on prediction and controlling of moisture content in buildings. Extreme disclosure to moisture is not only a common cause of major damage to building materials, it also can lead to unhealthy indoor living environments. So predicate and control moisture content provides a durable and long-term performance building with energy efficiency. Different methods (mechanical, simulation and graphical) for predicating and controlling the moisture content are described in this thesis. The comparisons between these methods have been carried out by taking into consideration of the importance and performance of each method and its tools.

Keywords: Moisture, moisture control, moisture prediction, moisture measurement.

ÖZ

Bu tez kapsamında, binalarda nem denetimi ve nem muhtevasının tesbiti konularında bilgiler sunulmaktadır. Bina konstrüsyonu bünyesinde yoğun miktarda bulunan nem, yapı malzemelerine verdiği hasar yanında, insan sağlığını olumsuz yönde etkilemektedir. Nem kontrolü, uzun vadede binaların servis ömrünü ve enerji etkinliği performansını sürdürülebilir kılmaktadır. Binalarda nem muhtevasının tesbiti için kullanılan ölçüm, önceden tahmin ve nem hareketlerinin bilgisayar ortamında canlandırılması, gibi yöntemler bu tez kapsamında araştırılmış ve belirlenen kriterlere göre mukayese edilip değerlendirmeler yapılmıştır.

Anahtar kelimeler: Nem, nem denetimi, nem tahkiki, nem ölçüm yöntemleri,

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I have the pleasure to dedicate this thesis to my Mom, you mean everything for me, without your love and understanding and
support; I wouldn't be able to make it. Thanks for your faith in me, and
for teaching me I should never surrender. You make me run out of words.

Daddy, your help and support always carrying me along, thanks for being patient and supportive.

My dearest brothers you always inspiring me for being hardworking enthusiastic to learn and never give up.

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Chapter1

INTRODUCTION TO MOISTURE IN BUILDINGS

1.1 Moisture

The Effect of moisture over the buildings could be categorised into 2 major types, indoor moisture in which can be sourced from unventilated bathroom and kitchen, condensation in the wall and windows, unventilated dryers, and even people, pets, and plants. However outdoor type is the most dominant source of moisture, which is imposed by climatic and natural factor outside the building. Therefore, identifying the sources and their impacts would be a fundamental requirement to prevent the effect of moisture.

In all buildings such as commercial or residential; health and comfort indoor environment is a significance of an architecture. But many residential people in building are complaining about unfavourable indoor condition and relative humidity that can make occupants uncomfortable in life cycle. Besides, high moisture humidity within building envelopes are other problem for buildings materials and it is destructive for material and produce some unhealthy environment due to the growing of mildew and mold.

Moisture causes some hazards to buildings make present health problems for occupant in building, like:

- Bowing and buckling
- Condensation
- Softening of interior surfacing material

- Standing water in ducts
- Stains
- Mold

The building envelops and walls can be affected from moisture in two ways, first; the usage of building causes some indoor humidity and indoor heat and moisture generation, Second; the humidity that is considered as external issue like; wind driven rain, air infiltration and inter air flow.

1.2 Aim and Objective

Architects should consider a high design building performance by predicating the problems that may occur from the first to the last steps of constructing. As it is mentioned in introduction one of these problems is moisture hazard. This paper describes prediction and calculation of moisture balance in building with some information about various methods, that is useful during the building design and construction process, by considering the geographical, geometric, material and etc. as general features of buildings.

Chapter 2 focuses on methods that are commonly used in terms of prediction and calculation of moisture content. These methods are mechanical, graphical, simulation software.

Mechanical method is categorized to resistance based, voltage based, thermal based methods and diagnostic methods. All these methods have sensors for measurement of moisture in building with different methodology of calculation, accuracy, durability, cost and etc.

Graphical methods are another way of computing moisture content that are dealing with some mathematically calculation. Graphical method is mainly categorized to Glaser and Dew – point by using different equation to compute the vapour flow of the surface.

Simulation software tools are another method of predicating moisture content that are programed by computer to simulate the whole condition of a building by considering all information such as energy balance, thermal comfort, HVAC systems, material of building and etc.

Aim of this paper is first, to find out the level of construction (before or after construction) to identify the best method that is appropriate for the level and gives the best result in terms of predicating and computing the moisture content.

1.3 Scope of Study and Limitation

The prediction and calculation of moisture is categorized into two steps. First, before construction and second, after construction and it is important as architect to analysis the each process which method is more useful in achieving the moisture prediction of buildings. Software and tools are important and deciding about the proper tool and software that are related to the design and construction of a building project is the job of the architectures that is described in this research. This thesis describes the methods and tools that are related to the prediction and calculation of moisture content in buildings and analyses some simulation program for design process in energy performance building. All methods, tools and software have their own pros and cons, which is also in the scope of this thesis to compare the limitation and facilitation.

The general information of the simulation software is provided in this research but detail information about the simulation software inputs and outputs are not provided. The information about the mechanical methods is provided but the detail information about tools is not in the scope of this research. Also the comparison of methods by each other to find out the best is one done.

Chapter 2

MOISTURE EFFECT ON BUILDING AND MEASURMENT, PREDICTION AND SIMULTION METHODS

2.1 Moisture Hazards in Buildings

Moisture hazards are the deterioration of the appearance or the performance of building materials when the moisture level surpasses the storage capacity of the material or the design operation conditions. The movement of moisture is a dynamic trend that needs various precautions in order to prevent the multiple moisture problems. A single prevention strategy is not enough to deal with all the factors that alter the moisture levels that accumulate within the building materials and components or on their surfaces. Moisture problems can cause noticeable damage to building materials or painful conditions indoors which indicate a future problem that is not yet visible. Some of these hazards are mentioned in coming sections. [1] [2] [3]

2.1.1 Bowing and buckling

It is the most comment indicator of moisture problem. It can occur on a wall, floor or ceiling and consists of a wave-like distortion. [2] [**3**]

Figure 1. Water on non-absorbent surface[1]

2.1.2 Softening of interior surfacing material

Another sign is softening of wall, ground or ceiling building material. This leads the materials to deteriorate, fall apart or peal off. [2] [3]

Figure 2. Softening of wall surfacing material [2]

2.1.3 Condensation

"Condensation is visible accumulation of water drops on non-absorbent surfaces. Condensation is most found in light fixtures, dripping out of electrical outlets, on metal ducts, and on other glass, metal, or plastic surfaces." [4]

Fugure 3. Water on non-absorbent surface surface [4]

Fugure 4. Water on non-absorbent surface surface [6]

2.1.4 Standing water in ducts

"Water in ducts is often caused by undiagnosed plumbing spills, but can also be caused by failure of the air conditioning condensate removal drainage system due to poor maintenance and or installation." [2]

Figure 5. Standing water in ducts [7]

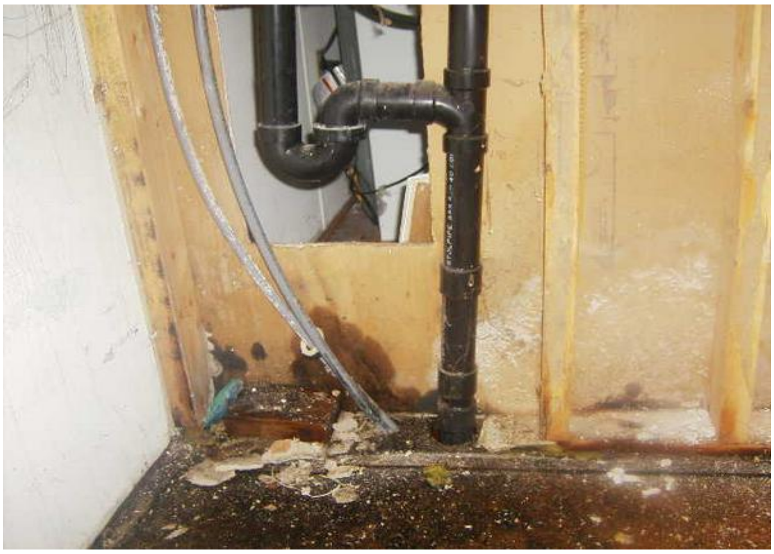


Figure 6. Standing water in ducts [8]

2.1.5 Elevated humidity

"Humidity is caused by critical element of human comfort in conditioned space. High interior humidity is generally defined as greater that 65% RH. High relative humidity increases condensation, as humid air comes into contact with surfaces at temperatures under the dew point." [2]

2.1.6 Odors

"Odors are indicative of long-term moisture problems that exist behind visible building material surfaces. Such odors can provide indications of physical damage, in addition to being an annoyance to occupants. Documentation of odors is challenging in that they are subject to the data gatherer and occupants' perceptions." [**2**]

2.1.7 Stains

Stain is the dirty marks of materials. It can appear along intersection of building material; on wall, .They are caused by water penetration of material or trough organic growth. [2] [3]

Figure 7. Discoloration of materials [65]

Figure 8. Discoloration of materials [9]

3.1.1 Rust

“Long-term condensation, rust occurs on metal surfaces such as nail and screw heads, air distribution grilles, and electrical components.” [3]

Figure 9. Rust on metal surfaces [10]

Figure 10. Rust on metal surfaces [11]

3.1.2 Mold

Mould is a fungus that requires water to grow. It can be toxic and can cause serious health problems. Moisture in buildings can lead to mould growth. [2] [3]

Figure 11. Mold on ceiling, wall and material [64]

Figure 12. Mold on ceiling, wall and material [64]

3.2 Moisture Measurement Methods in Buildings

The standardized method for prediction, calculation and evaluation of moisture is necessarily to make healthy environment of outdoors and indoor of building for peoples, There are several solutions for effect of moisture on buildings and hazards problems on buildings, this paper presents three numerical benchmark cases for the quality assessment of moisture models for calculating heat, air and moisture (HAM) transfer.

Calculate and predicate amount of moisture calculation before and after construction is important to prevent the hazards and construct a long life building. In this section we introduced some methods like mechanical, glazer and simulation and also we compared some standards that are used in these methods. [5]

3.2.1 Mechanical moisture measurement methods

Mechanical moisture measurement is categorized based on the measurement principle such as voltage, resistance, capacitance, microwave or thermal methods.

Voltage, resistance moisture measurement methods compute the electrical assets of materials that are vary depending on the moisture content. The microwave- based methods are working like capacitance method but in higher level of frequency. The thermal methods compute the temperature of material that is changed so that it can be caused by changing amount of moisture content. The capacitance-based methods are computed pin-less-type handheld moisture meters while the resistance – based methods are compute in probe-type handheld moisture meters.

"Resistance – based moisture sensors can compute the amount of moisture content for materials such as timber to compare to other materials." [5]

Other moisture measurement methods are used the electrochemical cell, which is triggered when gets wet and makes a voltage across a capacitor and resistor.

3.2.1.1 Resistance-based methods

Resistance-based methods measure the content of moisture in materials according to amount of moisture in electric resistance or dielectric property. The electrical resistance drops while conductance rises when the material moisture content increases. The volume of the resistance can change between several KΩ when wet, to over numerous hundred MΩ when dry. “There are some examples of resistance-type moisture sensor include brick ceramic, moisture pins, Duff moisture sensor, stone, nicked-wire, and moisture detection tape/cable.” [5]

One of the common ways to measure the moisture in material is to use moisture-pins, which measures the moisture not in a direct way but by measuring the electrical resistance of the material between two points. By using this method the possible temperature effect can be measured depending on the dielectric property of the material. Moisture-pins measures content of the moisture with an accuracy of ±2% (Garrahan 1988) [**5**]

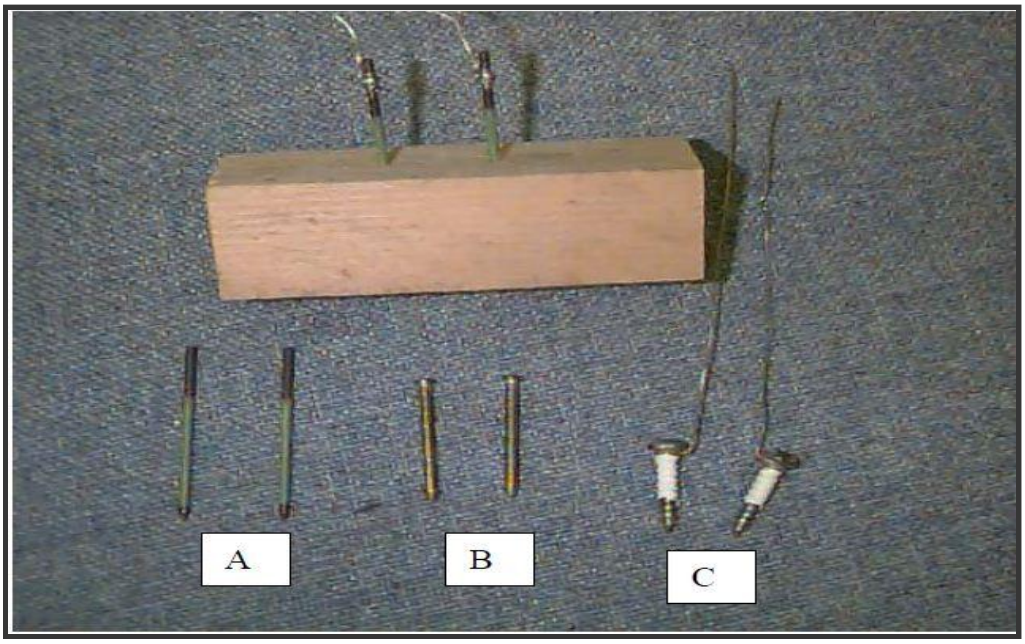


Figure13. A is an insulated pin, B is a non-insulated pin, and C is a stainless- steel screws. And the inserted pins into wood are insulated moisture pins. [5]

The most recommended way to install the moisture-pins sensors is to drill two holes 3.175 mm in diameter and they should be 2.45 cm apart on the mortar joint, concrete or timber. Most of the common moisture meters have probes with a spacing of 2.45 cm, and for other meters with different spacing the pins should be spaced accordingly. Once reached the desired depth with the drilling, the moisture pins are gently inserted into the wholes. The wires attached to the pins are protected with heat-shrinkable tubing or with high strength epoxy, but it is recommended to use UV (ultra violet) resistant Teflon for outdoor applications. Then the wires should be secured to the surface at a distance of 4 cm away from the pins screws and cables-ties. "A drainage loop (U-bend) should be included where the cables meet to prevent water from running down to the moisture pins (as shown in Figure 14). It is important to select the right position for the moisture pins where they do not meet water drops of other sensors." [**5**]

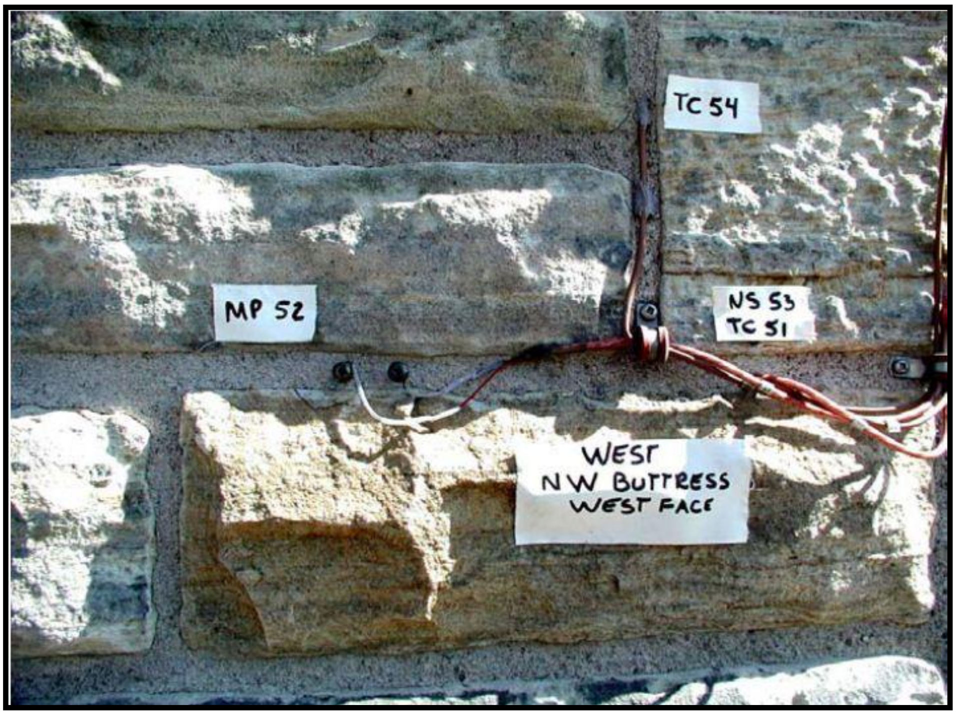


Figure 14. Stainless-steel screws (MP52) installed in a mortar joint and the drainage loop in the cables is attached to the screws [12]

"Brick-Ceramic and stone moisture sensors are an indirect way of measuring moisture by measuring the electric resistance crossways on a slight block of ceramic or stone material." [**5**] When stone and ceramic materials get wet, the electrical resistance decreases and vice-versa. Measurements in this method are based on the dielectric properties of the stone material or ceramic of the sensor's block. It is almost the opposite of the moisture-pin sensors, which are imbedded in the material. In Figure 14 the sensors are shown that they made-up by connecting in different sides of the stone or ceramic with two wires, which is made of conductive, silver epoxy (Figure 15).

Ceramic sensors are used to measure the wetness of a surface by putting them in various locations on the surface. These sensors could also be fixed in the material to measure the wetness of the material in depth. [**5**]

Stone sensors are used in stone masonry-wall applications to measure the wetness at a specific depth in the wall. "The small size of these sensors could be fixed through the typical 10-mm mortar joint. The ceramic and stone moisture sensors are measuring the wetness condition of the surface or material very quickly with less maintenance need.” [**5**]

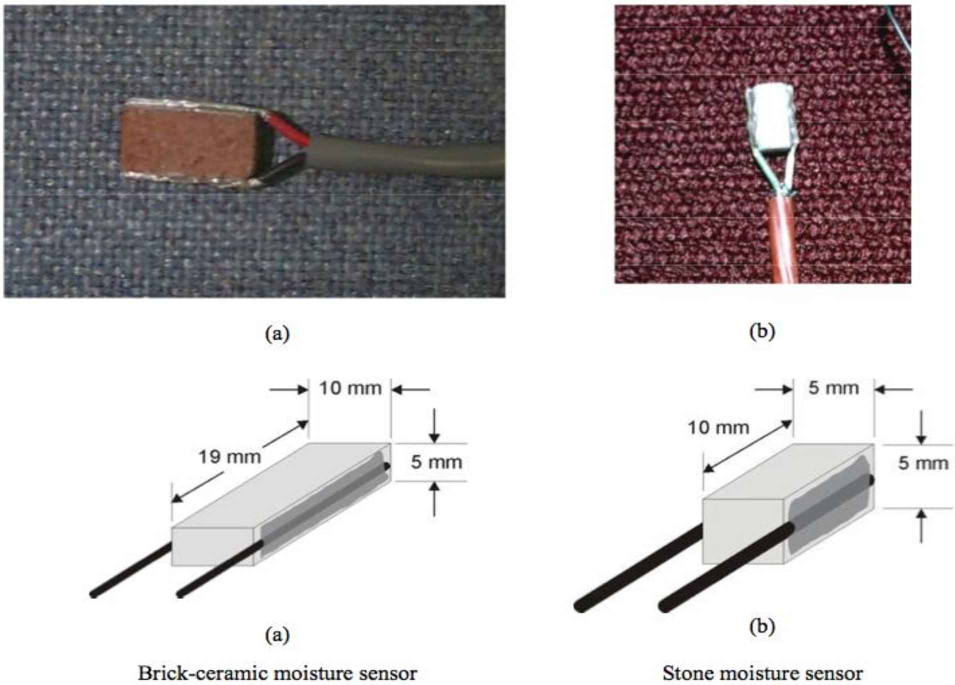


Figure 15. Common size and arrangement of the brick ceramic (a) and stone (b) moisture sensors [12]

One other sensor which is described by Duff (1996) “probe is made of two wires attached to the opposite sides of a 2 mm square and 20 mm long wood block, which has a close-grained structure to keep the inter-probe variation to a minimum. The Duff probe ignores the effects on measured data according to the variation of the dielectric property of the material, which is tested with moisture content and temperature. The concept of the Duff is almost same as the ceramic and stone sensors.” [**5**]

In 1999, Brandt and Hansen developed “two new sensors based on similar principles of the Duff probe and the moisture-pins. One of their probes is called ‘Moisture-Measuring-Disc’ which consists of two electrodes that are inserted in a 50 mm in diameter and 12 mm thick plywood disc, and the other probe is called

‘Moisture-Measuring-Dowel’ which is also consisting of two electrodes that are glued to a beech wood dowel 10 mm in diameter. These two probes each have a thermocouple that measures the temperature that is to be used for correcting the resistance measurement of the temperature effect.” [**5**]

The last moisture sensor is Gypsum-block that is categorized in the resistance-type sensor. It functions similar to ceramic and Duff moisture sensor. Gypsum is a hygroscopic (sensitive to moisture) material, which is developed for measuring the soil moisture to find out the time for irrigation. The service time for Gypsum is around 1-5 years and depends on how they become saturated according to (Larsen, 2004). [**5**]

3.2.1.2 Voltage-Based Methods

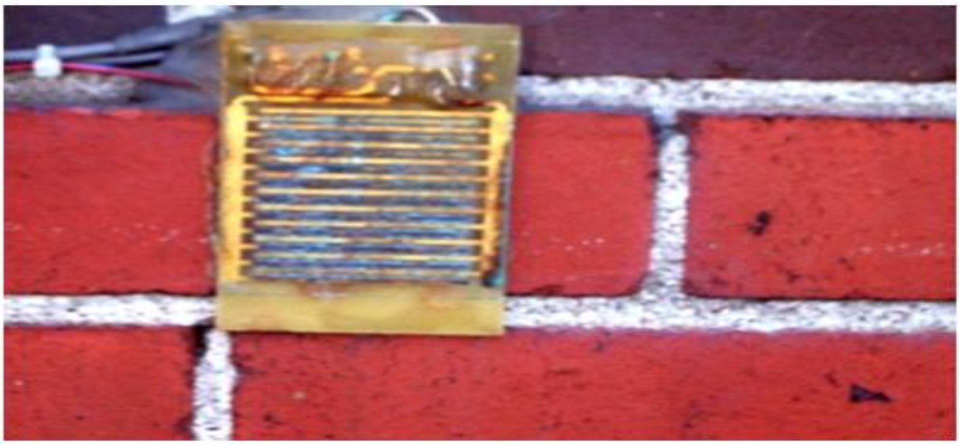
Voltage based methods used in moisture sensors for measuring moisture in positions of a DC (Direct current) voltage crossway of a known resistor. The output voltage is changing by the wetness such that when moisture increases, the voltage increases and vice versa. “There are some examples of voltage based methods include the printed circuit condensation sensor, Sereda moisture sensor, and the WETCORR monitoring system.” [**5**]

“The Printed Circuit Condensation Sensor (PCCS) consists of copper films placed in an interwoven pattern onto a fiberglass epoxy plate (Figure 16). The input of the sensor is 5 DC volts and the output is between 0-3 volts depending on the wetness of the area.” [**5**] The service time of this sensor is around 6 months because of the copper, which is not a durable material. The example of a 6 months copper is shown in (Figure 16) which not usable anymore.

The installation of PCCS is similar to Sereda moisture sensor, which is illustrated, in the next paragraph. For glass surface applications a RTV silicone sealant is used and for masonry applications, the sensors are glued to the surface by using a fast curing epoxy.

The Serada sensor is developed at the Institute for Research in Construction National Research Council Canada by Peter Serada (Serada et al, 1982) Serada is an electrochemical-cell sensor and used to specify time of wetness and drying of surfaces. This sensor is located at the frontage of the surface and can determine the wetting and drying of the surface.

a) Printed circuit condensation moisture sensor



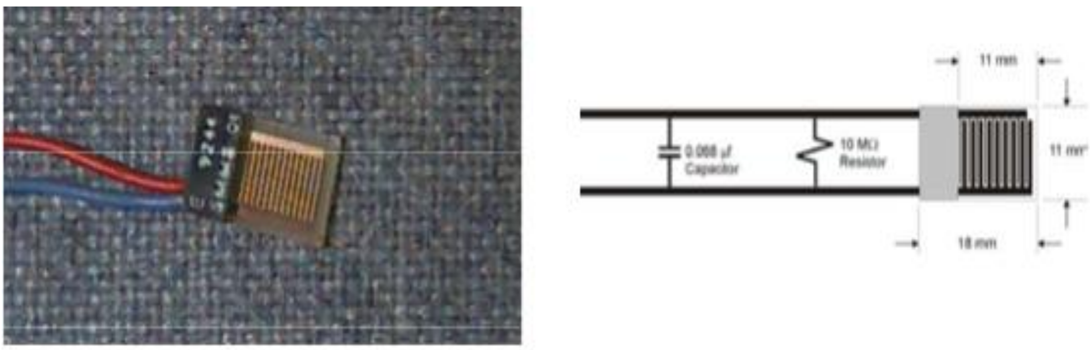
b) PCCS condition after 6-month on a façade

Figure 16.Printed circuit condensation moisture sensor (PCCS) [12]

The (Figure 17) shows the Sereda sensor "which is consist of copper with 35 μm meter thick and gold with 1 μm thick as electrodes deposited about 200 μm apart on a glass-reinforced polyester substrate to form a galvanic cell (Sereda et al, 1982).” **[**5**]**

“The sereda sensor when gets wet, the electrochemical cell is activated and makes a voltage across a 10-MΩ shunt resistor and 0.068 μf capacitor (see Figure 17).” [5]

The Sereda Sensor shows 2 to 4 mV when the surface is dry. Sereda sensor is more sensitive than ceramic moisture and also responds to great humidity surface but it is not long lasting and has a short service time (3 to 4 years for indoor). **[**5**]**



Sereda moisture sensor

Wiring diagram of Sereda sensor

Figure 17. Sereda moisture sensor and its wiring diagram [12]

The other sensor is WETCORR, which is developed by Norwegian Institute for Air Research that maps humidity and temperature on surfaces and within materials of building (NILU, 1994). The WETCORR is similar to Sereda sensor and has a thermistor temperature sensor, which is created by gold electrodes, which is placed into ceramic substrate. This sensor gives an electric current when it is wet. The WETCORR sensor is a system consisting of 64 sensors and a controller unit that is used to excite power for sensors and sampling data-logger. (NILU, 1994)

3.2.1.3 Thermal-Based Methods

The thermal - based methods are moisture measurement methods that try to apply the variation in the temperature of materials, which may appear by the occurrence of moisture. A wet material has a lesser temperature than a dry one, because the water has high thermal capacity.

a. -Thermal Heat-Sink Method

This method is described by Hagemaier (1970) to measure amount of moisture and thermal insulation in panels that used on space vehicles. In this method the wet material working likes a heat sink to check the temperature of wet or dry materials such that the wet one has the lower temperature than the dry one.

b. -Thermal Conductivity Method

Lucas (1974) developed a moisture sensor that is used for highway infrastructure. This method two moisture sensors is used, a thermal conductivity and a capacitance sensor.

The thermal conductivity sensor could measures thermal conductivity on the subject of soil moisture content. The thermal conductivity sensor contained of a thermistor and a heater that are made up on different sides of an alumina substrate.

The capacitance sensor contained of two sets of platinum electrodes, which are sheltered by glass on different sides of an alumina substrate. As the moisture changes the dielectric constant of the soil, the capacitance sensor could measure the moisture according to soil moisture content. [5]

3.2.1.4 Diagnostic Method

a. -Infrared Thermography Method

Infrared (IR) is known as a non – destructive method that electromagnetic radiation reflecting from surface is captured by infrared camera in a visual images.

This thermography has been used in many cases such as thermal bridges, air tightness of building envelopes and many other applications. This technology has advanced meaningfully in terms of size and cost.

These IR cameras are only detecting the variation of temperature and thermal effects that caused by presence of moisture in surface not sensing the moisture inside the wall.

Wet material acts as a heat sink because of high thermal capacity of water, so moisture creates temperature depression on the building envelope.

"The main advantage of thermography is the ability to assess moisture conditions over large areas of the building envelope." [5]

The following are examples of IR applications for measuring area of moisture anomalies in the envelop of buildings.

Balaras and Argiriou (2002) reviewed potential applications of IR thermography to inspect and perform non-destructive testing of building elements. Examples include locating missing or damaged insulation, thermal bridges, air leakage, moisture damages, and detecting cracks in concrete structures. They noted that an IR roof inspection could locate water-damaged areas with "good accuracy" and provide information to possible sources of the problem. Grinzato et al. (1998) presented a quantitative methodology for processing IR images to map defects in buildings. They reported example application results including mapping of moisture content. Rosina and Spodek (2003) presented a case study on IR thermography application to detect moisture distribution in historic masonry walls. Moisture distribution was obtained by comparing thermal images to observed moisture damage in the walls. They concluded that IR thermography is a promising non-destructive testing method that can be used to map damp areas in building envelopes. [**5**]

b. -Electromagnetic Wave Method

Microwave radiation technology is another method of determining the amount of moisture content in buildings. This method is quite expensive comparing to other methods with high accuracy. In this method measuring amount of moisture is done by producing an external processor controlled electrical magnetic field by low electrical power and high changing of polarity rate at the sample applicator. Now if a sample is located into this microwave field, the bipolar water molecules orientate and begin rotating. [6] [5]

3.2.1.5 Standards on Mechanical Moisture Measurement Methods

In today's modern life, standards act an important role in any aspects by providing desirable features of products and services such as environmental friendliness, efficiency safety, reliability, and quality and interchange ability while economical cost is taking into consideration.

Standards have many categories in building construction issues to provide better quality in terms of sustainability, energy efficiency, alternative energy, energy source, energy cost, environment concern, material conservation, climate changes and green building categories. In this section four standards are mentioned with their codes and illustration by their dependencies to moisture, environment and thermal characteristics in buildings. These four standards are, ASTM, ISO, ASHRAE and DIN.

Table 1. Some features of ISO, ASHRAE, ASTM, DIN standard [**7**] [**8**] [**9**] [**10**] [**11**] [**12**]

Feature	**ISO**	**ASHRAE**	**ASTM**	**DIN**
Countries	International	United state	United state	German
Languages	English-French and Russian	English	English	English-German
Newest Codes Related to moisture and released date	ISO 7730- 2005	ASHRAE 90.1-2010 62.2-2010	ASTM C324-01 (2007)	DIN 18195-2 1.4.2009

With professional organization that will be mentioned in the following that all these standards have related with methods as well, for examples must of the ASTM, ISO, DIN standards, have building and construction code comfort the mechanical methods and sensors in the method that is usable for durability of buildings. And also ASHRAE and ISO standard have related with simulation program

a. -ASTM standard

ASTM (American Society for Testing and Materials International) founded in 1898 as a non-profit organization that develops voluntary agreements of standards for materials, products and services. ASTM standards are used in development, product testing, quality systems and commercial businesses around the world.

ASTM has more than 150 entries in “moisture determination” and “relative humidity”. And it is give you the tools you need to construction and designs building that satisfy by over 1,300 ASTM construction standards that have international code.

Relative humidity (RH) is measurement of moisture in the air and contains huge amount of techniques; other than RH, there are some measurement techniques in water leakage, water vapor transmission, building airflow and moisture in building materials. Extra moisture related standards have been spread by ANSI, ASHRAE.

ASTM standard describes the application of almost all moisture sensor in mechanical methods, for example ASTM G84-89 (2005) application of moisture sensor in voltage method, and ASTM Standard C 1153 -97 (2003) Standard is practice applies to techniques that work infrared imaging to determine the location of wet insulation in roofing systems at night, ASTM E168-99 (2004), ASTM listed D 4643-08, F 1869-10, D 1558-10, C 1699-08, C 1363-11, D 4444-08, C1498-04 and etc., that you can check in table 2.

Next table (table 2) has the most related codes of ASTM standard to moisture in building and materials, humidity resistance, thermal insulation, water vapor and many other associated codes that are used in buildings. And these abbreviations are used: (STM) Standard Test Method. [**13**] [**11**]

Table 2. ASTM (American society for testing and materials) standards relevant to moisture or humidity measurement [**14**] [**13**] [**11**]

ASTM	**Title**
C70-06	"STM for Surface Moisture IN fine Aggregate"
C128-07a	"STM for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate"
C324-01 (2007)	"STM for Free Moisture in Ceramic White ware Clays"
C566-97 (2004)	"STM for Total Evaporable Moisture Content of Aggregate "by Drying
C755-03	"SP for Selection of Water-Vapor Retarders for Thermal Insulation"
C1104/C1104M-00 (2006)	"STM for Determining the water-vapor Sorption of Un faced Mineral Fiber Insulation"
C1136-08	"SS for Flexible, Low performance Vapor Retarders for Thermal Insulation"
C1258-08	"STM for Elevated Temperature and Humidity Resistance of Vapor Retarders for Insulation"
C1601-08	"STM for Field Determination of Water Penetration of masonry wall Surfaces"
D644-99 (2007)	"STM for Moisture Content of Paper and Paperboard by Oven Drying"

D1864-89 (2002)	"STM for Moisture in Mineral aggregate Used on Built-up Roofs"
D2216-05	"STM for Laboratory Determination of Water (moisture) content of Soil and Rock by Mass"
D2247-02	"SP for Testing Water Resistance of Coating in 100 % Relative Humidity"
D2987-88 (2006)	"STM for Moisture Content of Asbestos Fiber"
D3017-04	"STM for Water Content of Soil and Rock in Place by Nuclear Methods (shallow Depth)"
D4178-82 (2005)	"SP for Calibrating Moisture Analyzers"
D4230-02 (2007)	"STM for Measuring Humidity with Cooled Surface Condensation (Dew-point) Hygrometer"
D4263-83 (2005)	"STM for Indicating Moisture in Concrete by the Plastic Sheet Method"
D4442-07	"STM for Direct Moisture Content Measurement of Wood and Wood-Base Materials"
D4444-08	"STM for Laboratory Standardization and Calibration of Hand-Held Moisture Meters"
D4959-07	"STM for Determination of Water (Moisture) content of Soil by Direct Heating"
E96/E96M-05	"STM for Water-Vapor Transmission of Materials"
E154-08a	"STM for Water-Vapor Retarders Used in Contact with Earth Under Concrete Slabs, on walls, or as Ground Cover"
E241-08	"SG for Limiting Water Induced Damage to Buildings"

E331-00	“STM for Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference”
E337-02 (2007)	“STM for Measuring Humidity with a Psychrometer (the Measurement of Wet- and Dry-Bulb Temperatures)”
E398-03	“STM for Water-Vapor Transmission Rate of Sheet Materials Using Dynamic Relative Humidity Measurement”
G84-89 (2005)	“Standard practice for measurement of time-of-wetness on surfaces exposed to wetting conditions as in atmospheric corrosion testing.”
D 4444-08	“Standard test method for laboratory standardization and calibration of Hand-Held moisture meters”
C1498-04	“Test method for Hygroscopic Sorption Isotherms of building materials.”
C1699-08	“Test method for moisture retention curves of porous building materials using pressure plates.”
F1869-10	“Test methods for measuring moisture vapour emission rate of concrete subfloor using anhydrous calcium chloride.”
C1363-11	“Test method for thermal performance of building materials and envelope assemblies by means of a hotbox apparatus.”
C11-53-97 (2003)	“Standard practice for location of wet insulation in roofing systems using infrared imaging.”

b. - ISO standard

ISO (International Organization for Standardization) is a well-known organization that is founded in 1946 by 25 countries with the purpose of “facilitate the international coordination and unification of industrial standards". ISO has more than 18.500 international standards on different subjects and this number is increases every year by approximately 1100 new standards.

“The ISO standards are mainly categorized by ICS, classified by subject in accordance with the International Classification for Standards or TC (sorted according to the ISO technical committee responsible for the preparation and/or maintenance of the standards).” [**9**]

We mainly focus on building construction, building environment design, and some thermal comfort standards that are illustrate in the following table.

The table 8 is addressed some standards that are mainly used in building before and after construction. In modern lifestyle people spend about 90% of their time indoors, so the air purity is an important issue in today’s life that needs to care about humidity, and thermal comfort in indoor environment. These issues vary among different countries because of different climate, so that; the usage of these standards is depending on the country.

The following are other moisture related of ISO standard with mechanical methods for example: ISO 7730: “Moderate thermal environmental – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort”; EN ISO 7730: “Moderate thermal environmental – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort”; ISO/DTR 21932: “Building construction--sustainability in building construction – terminology” and for checking some other DIN moisture standards check table 3. [**15**] [**9**]

c. -DIN standard

DIN standard (Deutsches Institut fur Normung) in English (German Institute for Standardization) is a non-governmental institute that is accepted by the German government to represent German fondness at European and international standards it encourage rationalization, safety, quality guarantee, and environmental protection as well as enlightening communication between manufacturing, science, technology, government and the communal zone.

DIN publishes draft standard to get comments from public and before final publication standard is reviewed by considering comments. Published standards are checked and reviewed every five years at least. As it mentioned before DIN is a German organization but most of the DIN standards are available in English version.

DIN has over 12,000 standards in different topics such as: “building and civil engineering (materials of building, construction contract procedures (VOB), soil testing), material testing (machine testing, semiconductors, plastics), physical measurements and units, process engineering, etc.” [8]

In the following, standard codes that are used in the mechanical methods are listed: [16] [17]

DIN is categorized to the following abbreviations

- DIN # (German standard),
- E DIN # (draft standard),
- DIN V # (preliminary standard),
- DIN EN # (English version of German standard),
- DIN ETS # (European Telecommunication standard),
- DIN ISO # (German edition of ISO standard),

- DIN EN ISO # (if standard adopted as a European standard) [**8**] [**12**]

Next table (Table 3) shows the most related codes of DIN standard to moisture content and waterproofing of buildings. [**16**]

Table 3. DIN (German Institute for Standardization) standards [**16**] [**17**] [**8**] [**12**]

DIN Standard	Title
DIN 51718	Determining the moisture content of solid fuels
DIN 10304-2	Determination of moisture content and dry substance of glucose syrup; vacuum oven method
DIN 18195-1	Waterproofing of buildings and structures; general, terminology. Publication date: 1.8.1983
DIN 18195-2	Waterproofing of building- part 2: Materials. Publication date 1.4.2009
DIN 18195-5	Waterproofing of buildings - Part 5: Waterproofing against non-pressing water on floors and in wet areas; design and execution. Publication date 1.8.2000
DIN 18195-7	Waterproofing of buildings - Part 7: Water-proofing against pressing water from the inside, dimensioning and execution.
DIN 18195-8	Waterproofing of buildings - Part 8: Water-proofing over joints for movements.1.3.2004
DIN 18195-9s	Waterproofing of buildings - Part 9: Penetrations, transitions, connections and endings.
DIN 18195-10	Waterproofing of building-part 10: Protective layers and protective measures. Publication date: 1.3.2004
E DIN 18195-100	Waterproofing of buildings - Part 100: Proposed amendment to the Standards DIN 18195 Part 1 to 6. Publication date: 1.6.2003

DIN 12691	Flexible sheets for waterproofing - Bitumen, plastic and rubber sheets for roof waterproofing - Determination of resistance to impact. Publication date 2010
DIN EN 1108	Flexible sheets for waterproofing - Bitumen sheets for roof waterproofing - Determination of form stability under cyclical temperature changes. 1.10.1999
DIN EN 1931	Flexible sheets for waterproofing - Bitumen, plastic and rubber sheets for roof waterproofing - Determination of water vapour transmission properties. Publication date 1.3.2001
DI EN 1110	Flexible sheets for waterproofing - Bitumen sheets for roof waterproofing - Determination of flow resistance at elevated temperature. Publication date 1.10.1999

3.3 Moisture Prediction Methods in Buildings

The three well-known manual design tools for estimating the condensation are Glaser diagram, dew-point method, and kieper diagram. All these method are using some calculation (not simulation) of the hygrothermal (heat and moisture) appropriateness of an exterior envelops (roofs, ceilings, and walls) In other words all three methods are a steady-state design tools that are using graphic methods for evaluating interstitial drying and condensation exterior envelopes by calculating the simple vapor diffusion equation with pressure of the saturation that are dealing with the temperature within the envelop.

3.3.1 Graphical methods

The weakness of graphical method is in calculating of the transfer of the moisture techniques except diffusion of vapor and eliminates storage of moisture in building.

Differences between Glaser and Dew point are coming from the formulation of the vapor diffusion equation, which is illustrated in the coming section.

"The dew point method mainly used in North America, and the Glaser diagram, usually used in Europe and elsewhere". [7] [18] [19]

3.3.1.1 Glaser

The Glaser method is explained in some international technical standards such as EN ISO 13788 (2002) and SN 730540-4 (2005). One of the usages of this method is for compact roof assembly that is mainly designed on the Glaser calculation. [18]

Glaser is usually used in Europe and its equation is shown below:

W = - (δ^, /μ^,) Δp/d (eq.1. [19])

Where

"δ^, = Diffusion coefficient of water vapor in air, s, and

μ^, = Diffusion resistance factor of the material."

The Glaser method is not dealing with hygroscopic sorption and liquid transport, so it is limited to lightweight structures. Problems, such as moistures in construction, precipitation, and rising damp are not in the scope of Glaser method.

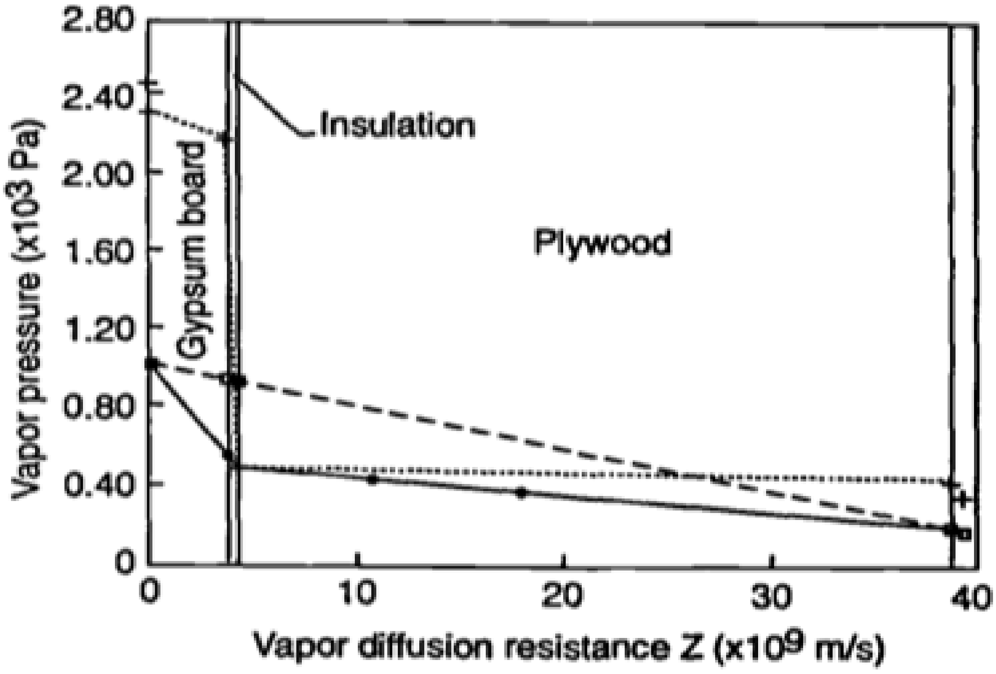


Figure 18. Glaser diagram for example shows the wall without vapor. Dotted line means saturation of vapore pressure. Soil line is the last computation of vapor pressure and the computation of vapor pressure in first step is shown as dashed line [26]

"The resistance to water vapor diffusion factor is the ratio of diffusion resistance factor of the material and the resistance of a layer of air of equal thickness." [**19**]

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

$$\delta=\delta/\mu \qquad \text{(eq. 2. [19])}$$

"By substituting δ in eq. 7 shows that diffusion coefficient δ and permeability eq. 3 are the same." [**19**]

So now resistance of vapor diffusion is

$$Z=d/\delta$$

"The only difference between conventional dew point and Glaser diagram is about the horizontal axis of the diagram. Instead of using thickness of the materials, the Glaser diagram uses the vapor diffusion resistance in horizontal axis (Fig. 18 shows a repeat of Example 2). So, larger resistance of material cause most prominently. By this way of displaying, the individual vapor pressures need not to be calculated because the vapor pressure profiles are transformed into straight lines. In the example of the wall without vapor retarder and condensation on the ply- wood, the vapor pressure profile consists of two straight-line segments. The saturation vapor pressure still needs to be computed from temperatures, as in the dew point method." [**19**]

3.3.1.2 Dew – point

Dew point can be calculated by the following diffusion equation:

$$W = -\mu \Delta p/d \quad \text{(eq. 3. [19])}$$

Where

"W = Vapor flow per unit of area, kg/m¬2.s (grain/ft2.h),

μ = Water vapor permeability, kg/m . s . Pa or s (perm. in.) 2,

p =Vapor pressure, Pa (in. Hg), and

d = Flow path or thickness of the material, m (in.)." [**19**]

For better understanding of dew point method we can see two examples in next sections. [**18**]

EXAMPLE 1: WALL WITH RETARDER VAPOR

The dew point method is explained in this example. "A frame wall construction with gypsum board, glass fibber insulation, wood siding, plywood sheathing is used that can be seen in table 4. Also the wall has a vapor retarder on the warm side of the cavity." [**19**]

The following data is assumed

"2I °C (70°F), 40% (indoor relative humidity)

-6.7°C (20°F), 50% (outdoor relative humidity)" [**19**]

Table 4wall vapor and thermal diffusion properties this example. [**19**]

	Thermal Resistance			Diffusion Resistance	
Air Film or Material	(h·ft²·°F/Btu)	(m²·K/W)	Permeance,[a] perm	$Z = d/\mu$, 1/perm	$Z = d/\delta$, 10^9 m/s
Air film (still)	0.68	0.12	160[b]	0.0063	0.11
Gypsum board, painted	0.45	0.08	5	0.2	3.5
Vapor retarder	...	...	0.06	17	290
Insulation	11	1.9	30	0.033	0.6
Plywood sheathing	0.62	0.11	0.5	2	35
Wood siding[c]	1	0.18	35	0.029	0.5
Air film (wind)	0.17	0.03	1000[b]	0.001	0.02
Total	13.92	2.42	...	18.94[d]	329.73[d]
				2.27[e]	39.73[e]

[a]1 perm = 1 grain/ft²·h·in. Hg.
[b]Approximate values; permeance of surface air films is very large compared to that of other materials and does not affect results of calculations.
[c]Approximate values; permeance reflects limited ventilation of back of siding.
[d]Total diffusion resistance of wall with vapor retarder.
[e]Total diffusion resistance of wall without vapor retarder.

The following steps illustrated this example:

Step1:

Calculating the temperature drop across each material.

$$\Delta T_{material} / \Delta T_{wall} = R_{material} / R_{wall} \quad \text{(eq. 4. [19])}$$

Table 5. This table shows the result of temperature for drops and at each surface. [**19**]

Air Film or Material	Temperature, °C (°F) Drop	Temperature, °C (°F) Surface	Saturation Vapor Pressure, Pa (in. Hg)
Indoor air			
		21.1 (70)	2503 (0.7392)
Surface air film	1.3 (2.4)		
		19.8 (67.6)	2305 (0.6807)
Gypsum board	0.9 (1.7)		
		18.9 (65.9)	2174 (0.6419)
Vapor retarder	0		
		18.9 (65.9)	2174 (0.6419)
Insulation	22.0 (39.5)		
		−3.1 (26.4)	486 (0.1434)
Plywood sheathing	1.2 (2.2)		
		−4.3 (24.2)	443 (0.1309)
Wood siding	2.0 (3.6)		
		−6.3 (20.6)	381 (0.1124)
Surface air film	0.4 (0.6)		
		−6.7 (20)	371 (0.1096)
Outdoor air			

[a]Temperature drop across the air film or material. Surface temperatures and saturation vapor pressures are taken at the interface for each set of air films or materials.

Step 2:

"Finding the saturation vapor pressures [Pa (in. Hg)] related with the surface temperatures." [**19**]

"Table 5: lists the saturation vapor pressures for this example." [**19**]

Step 3:

"The Vapor pressure drops across each material can be calculated by

Z_{wall} =329.73 109 m/s (18.94 perm-1)" [**19**] (eq. 5. [**19**])

By calculating the relative humidity and saturation vapor pressure of indoor and outdoor, the total vapor drop across the wall can be found (see Table 5).

$$\Delta P_{wall} = P_{indoor} - P_{outdoor}$$

$$=(40/100)\ 2503-(50/100)\ 371$$

$$=1001-186=815 \text{ Pa } (0.2409 \text{ in. Hg})$$

“The vapor pressures at the surfaces of each material can be determined from the vapor pressure drops.” [**19**]

Step 4:

Figure 19 shows the ca [**19**]lculated vapor pressures and saturation.

No condensation is shown because; it is not more than the saturation of vapour pressure.

Vapor flow is uniform throughout the wall and can be calculated as follows

$$W= \Delta P_{wall} / Z_{wall}$$ (eq. 6. [**19**])

“For this example, W=815/ (329.73 109) = 2.5 10-9 Kg/m2.s (0.013 grain /h. ft2) which is very small amount of water vapor flow.” [**19**]

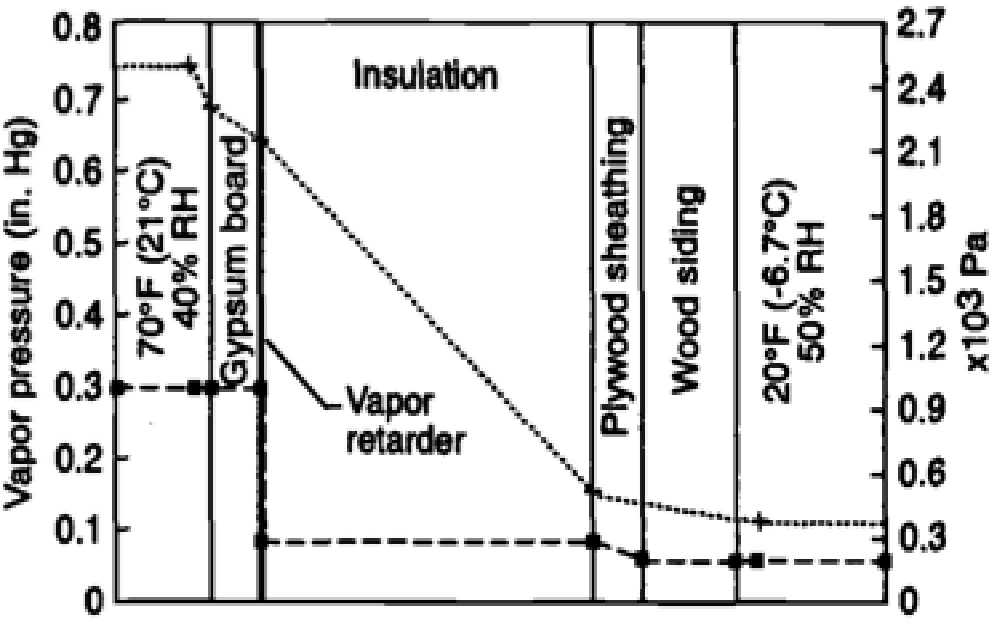


Figure 19. Dew point method; example shows the wall with vapor pressure, last computation Dashed [26]

EXAMPLE 2: WALL WITHOUT VAPOR RETARDER

"Wall in the second example is identical except for the omission of the vapor retarder." [**19**]

"In this example the wall is the same as Example 1 but without vapor retarder. The vapor retarder has insignificant effect on temperatures, when air movement is not considered; saturation vapor pressures and temperatures are the same as in the wall in Example 1. So the step 1 and 2 are the same so we skip to step3" [**19**]

Step 3:

"The total vapor diffusion resistance of this wall is as follows" [**19**] (see Table 4)

"Z_{Wall} =39.73 109 m/s (2.27 perm-1) " [**19**]

Table 6. Calculation and lists the result for the example that has the vapor pressures with retarder of vapor inside the wall. [**19**]

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure [Pa (in. Hg)]	
		Drop	Surface
Indoor air (40% RH)[b]			
	2503 (0.7392)		1001 (0.2957)
Surface air film		0.3 (0.00008)	
	2305 (0.6807)		1001 (0.2956)
Gypsum board		8.6 (0.0025)	
	2174 (0.6419)		992 (0.2930)
Vapor retarder		717.9 (0.2120)	
	2174 (0.6419)		274 (0.0810)
Insulation		1.4 (0.0004)	
	486 (0.1434)		273 (0.0806)
Plywood sheathing		86.2 (0.0254)	
	443 (0.1309)		187 (0.0552)
Wood siding		1.2 (0.0004)	
	381 (0.1124)		186 (0.0548)
Surface air film		0.04 (0.00001)	
	371 (0.1096)		186 (0.0548)
Outdoor air (50% RH)			

[a]Vapor pressures are taken at the interface for each set of air films or materials.
[b]RH is relative humidity.

The initial calculations are shown in Table 7.

Step 4:

“By checking the saturation pressure we can see that the calculated vapor pressure on the interior surface of the sheathing [915 Pa (0.2702 in. Hg)] is well above the saturation pressure at that location [486 Pa (0.1434 in. Hg)]. So it is obvious that we have condensation probably on the surface of the sheathing.” [**19**]

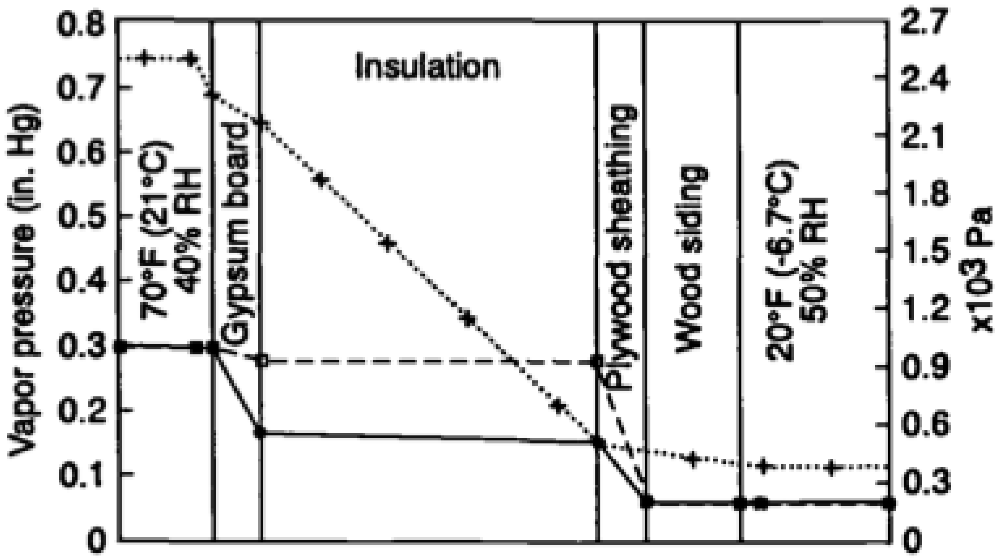


Figure 20. Dew point method; example shows the wall without vapor pressure profile identified as vapor pressure. Dashed line is the first calculation of vapor pressure; dotted line is saturation vapor pressure; solid line is the last calculation of vapor pressure [26]

To find out the location and rate of condensation we need to do Step 5 and 6.

Step 5:

"The calculated vapor pressure is exceeds the saturation vapor pressure by the largest quantity at the interior surface of the plywood sheathing as it is shown in figure 2, so this is the most likely place for occurring the condensation. Vapor pressure should equal saturation at the location of the surface with condensation." [**19**] (See Table 7)

Table 7the First and last computation inside the wall of its vapor pressures without inside wall minus vapor retarder. [**19**]

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure, Pa (in. Hg)	
		Drop	Surface
INITIAL CALCULATION			
Indoor air (40% RH)			
	2503 (0.7392)		1001 (0.2957)
Surface air film		2.2 (0.0007)	
	2305 (0.6807)		999 (0.2950)
Gypsum board		71.9 (0.0212)	
	2174 (0.6419)		927 (0.2738)
Insulation		12.0 (0.0036)	
	486 (0.1434)		915 (0.2702)
Plywood sheathing		718.9 (0.2123)	
	443 (0.1309)		196 (0.0579)
Wood siding		10.3 (0.0030)	
	381 (0.1124)		186 (0.0549)
Surface air film		0.4 (0.0001)	
	371 (0.1096)		186 (0.0548)
Outdoor air (50% RH)			
FINAL CALCULATION			
Indoor air			
	2503 (0.7392)		1001 (0.2957)
Surface air film		13.4 (0.0040)	
	2305 (0.6807)		988 (0.2917)
Gypsum board		430.4 (0.1271)	
	2174 (0.6419)		557 (0.1646)
Insulation		71.7 (0.0212)	
	486 (0.1434)		486 (0.1434)
Plywood sheathing		295.8 (0.0874)	
	443 (0.1309)		190 (0.0560)
Wood siding		4.2 (0.0012)	
	381 (0.1124)		186 (0.0548)
Surface air film		0.1 (0.00004)	
	371 (0.1096)		186 (0.0548)
Outdoor air			

Step 6:

"The alteration of vapor pressure on the plywood sheathing adjusts all other vapor pressures together with the vapor flow across the wall. Calculation of vapor pressures is similar to what we had in step3, the only differences is that the wall is now divided into two sections: one section on the interior of the condensation that is, the insulation and gypsum board and the other one is on the exterior that is, wood siding and plywood sheathing." [**19**]

"The vapor pressure drop over the first section of the wall is" [**19**]

"$\Delta p1 = 1001 – 486 =515$ Pa (0.152 in. Hg)" [**19**]

And that over the second section is

"Δp2 = 486 – 371 = 115 Pa (0.034 in. Hg)" [**19**]

The vapor diffusion resistances of both sections of the wall are

"Z1 = (0.11 + 3.5 + 0.6) 109 = 4.21 109 m/s (0.24 perm-1)" [**19**]

"Z2 = (35 + 0.5 + o.o2) 109 = 35.53 109 m/s (2.03 perm-1)" [**19**]

The vapor pressure drops can now be calculated from

$$\Delta p_{material} / \Delta pI = Z_{material} / Z\ I \qquad I = 1.2 \qquad \text{(eq. 7 [19])}$$

"So, the final calculation of vapor pressure can be seen on table 7. The vapor pressure is not exceeds than the saturation vapor pressure anymore, so the condensation plane was chosen correctly." [**19**] (See figure 2)

"The vapor flow into the wall from the indoor air increased when the vapor pressure is low at the plywood surface while flow from the wall to the outside is decreased, so the vapor flow is no longer the same throughout the wall." [**19**]

"The difference between the two flows is the rate of moisture accumulation." [**19**]

"W c = Δp 1 /Z 1 - Δp 2 /Z 2 = 515/(4.21 109) – 115/(35.53 109) =11910-9

Kg/s.m2 (0.61 grain / h. ft2)" [**19**]

"In this example, the plywood surface is under the freezing temperature, and this can cause the moisture to frost. About a week of condensation at this rate would increase the average moisture content of the plywood by 1%." [**19**]

The dew point method can be summarized as follows:

"Surface temperatures and calculate temperature drops.

1. Compute the related saturation vapor pressures.
2. Compute vapor pressure and vapor pressure drops.

3. Calculate if saturation pressure is above the pressure at all surfaces; therefore no condensation is shown vapor across the wall, maybe determined if desired. If condensation is shown, do the following steps.
4. Choice condensation surface; vapor pressure at this surface parallel the saturation vapor pressure.
5. Recomputed vapor pressure; if any vapor pressures are above saturation, step 5, and step 6 should be repetitive with a different condensation surface.
6. If necessary, compute ate of condensation.” [**7**] [**19**]

3.3.2 Numerical Methods (Simulation)

International Energy Agency developed a project named as Building Energy Simulation Test ("BESTEST") for practical implantation procedure of buildings. This project was developed to test whole building energy, systematically by simulation programs.

Building energy simulation programs have been developed and improved in the past 50 years, and there are wide varieties of software tools that exist for evaluating energy efficiency, renewable energy, and sustainability in buildings. All the capabilities of building energy performance simulation programs improve in the following categorizes; zone load; day lighting, building envelope and solar; ventilation, in filtration and multi-zone airflow; general modeling features, renewable energy systems; HVAC equipment; HVAC systems; electrical systems and equipment; environmental emissions; climate data availability; economic evaluation; results reporting; validation; and links to other programs, user interfaces, and availability.

For building construction and design, designers need tools or programs that provide some facilities for constructions, In this section some information about tools such as users, input, output, expertise required, audience, computer platforms, strengths, technical contact, weaknesses, and availability is provided which is mostly related to effects of moisture in building. [**20**] [**21**] [**22**] [**23**]

3.3.2.1 1D-HAM

Working with 1D-coupled heat, air and problems with moisture transport mostly in multi-layer wall like porous. This program returns a data file for values per hour over the year. [**24**]

3.3.2.2 BSim

"Measuring the indoor climate, energy for designing the heating, cooling and ventilation plants." [**20**] Bsim comprise following programs:

- SimView (graphical simulation interface)
- tsbi5 (simultaneous thermal and moisture building simulation)
- XSun (dynamic solar and shadow simulation and visualisation)
- SimLight (daylight calculation tool)
- SimDXF (CAD import facility)
- SimPV (building integrated PV-system calculation) [**20**]

3.3.2.3 ENER-WIN

This software can perform the energy examination for 8769 hours per year for 98 zones and 20 different window, wall and computes HVAC loads, transient heat flows, energy consumption, life-cycle cost, and charges of demand and temperatures of floating point in unconditioned zones. [**20**]

3.3.2.4 DOE-2

This software provides the energy analysis for building by calculating performance of energy and life cycle cost of operation to get energy efficient design. [**25**]

3.3.2.5 DeST

DeST is a simulation toolkit for designers that developed for serving HVAC engineers. This software as an annual analysis program also helps architectures to optimize their thermal performance. DeST has following simulation steps:

- Building thermal process
- System scheme analysis

- Analysis of system by AHU
- Pipe and duct network
- Analysis of plant

By the above simulation steps DeST provides perfect result for designing the system of a building.

DeST also provides computations on multi-zone heat and mass balance, building thermal, 3D dynamic heat transfer methodology and dynamic simulation method coupling CFD. [**20**]

3.3.2.6 PsyChart

PsyChart calculates the moist air state; this software has a graphical interface to get all common air – conditioning processes. [**26**]

3.3.2.7 HAMLab

HAMlab (Heat, Air and Moisture simulation Laboratory) is a group of functions in Simulink, Matlab, Femlab that contains:

- HAMSYS: building systems models
- HAMOP: optimal operation
- HAMDET: detailed (up to 3D) building physics models
- HAMBASE: HAM transport in multi-zone building models [**27**]

3.3.2.8 FRAME4

Frame4 uses 2D analysis to compute the heat transfer through building components.

Frame4 analyses doors, windows, walls and roofs by getting the data entry by different formats.

The output is shown graphically to determine the heat transfer and condensation.

According to REFRENCE The Canadian Standard Association and U.S. National Fenestration Rating Council recognize FRAME as the one acceptable computer program to define doors, curtain walls and heat transfer through opaque portions of windows. [**28**]

3.3.2.9 Frame Simulator

Frame calculates the thermal transmittance in building materials and windows. Frame can:

- Analyzes the heat flows through building materials.
- Estimates temperature of surface and define the condensation problems.
- Determines weak points in frames of window.
- Computes the thermal transmittance UF.
- Computes linear conductance Lf2d of any type of frame of window.
- Computes Uw thermal transmittance of fenestration.
- Frame simulates the transference of heat using 2D method by conforming to ISO 10077-2. [**29**]

3.3.2.10 Design Advisor

Design Advisor is an energy simulator that models energy, day lighting performance, and comfort by giving the cost estimation of utilities in long term. Design Advisor is a simple and fast tool, which can be used by non-technical designers.

Results are useful in design and conceptual phase on energy model of the envelope system in a building. The estimation of the energy model is based on library of climate data for 30 different cities. [**30**]

3.3.2.11 VISION4

VISION4 is part of FRAMEplus Toolkit for analysis of thermal for walls, windows, and doors. It calculates the velocity field within window glazing cavities to get better prediction of condensation resistance. VISION4 also can simulate thermal and optical performance of glazing systems and gives data on the temperature and energy flow that causes from environmental condition. VISION4 by combing with FRAME can determine condensation resistance, U-value and solar heat gain coefficient of doors and windows. VISION4 was used to produce the information of windows in ASHRAE handbook of fundamentals. [**31**]

3.3.2.12 UMIDUS

UMIDUS analyses hygrothermal performance of building materials with different climate conditions. This software compute moisture and temperature in low – slope roofs and multi – layer walls while can calculate the mass and heat transfer. Building different construction elements and compare them by mass flow, heat flux and moisture content characteristics is an ability that is given to user in this software.

The output of software is given in graphs and building parameters. [**21**]

3.3.2.13 Therm

Therm can analysis the two-dimensional heat transfer through building materials. It has a graphical user interface that allows user to draw cross section of building products then by applying the heat transfer algorithms the results are displayed graphically. [**32**]

3.3.2.14 PUtility Psychrometric

PUtility Psychrometric is utility software that calculates moist air state by showing it in a psychometric chart. The software by getting the value of dry-bulb temperature and humidity through a CSV file as an input can plot the result data on a chart.

The following simulation programs are selected from 25 software, which are more powerful and related to moisture content prediction. for more information the screenshot of each software is provided. [**33**]

3.3.2.15 AnTherm

AnTherm (Analysis of Thermal behavior of Building Construction Heat Bridges) computes heat flows, vapor diffusion flow, temperature distribution in building structures. AnTherm gives a reliable evaluation of thermal performance under the European standards (EN ISO).

AnTherm easily generate the geometrical models with graphic input display of building construction. [**34**]

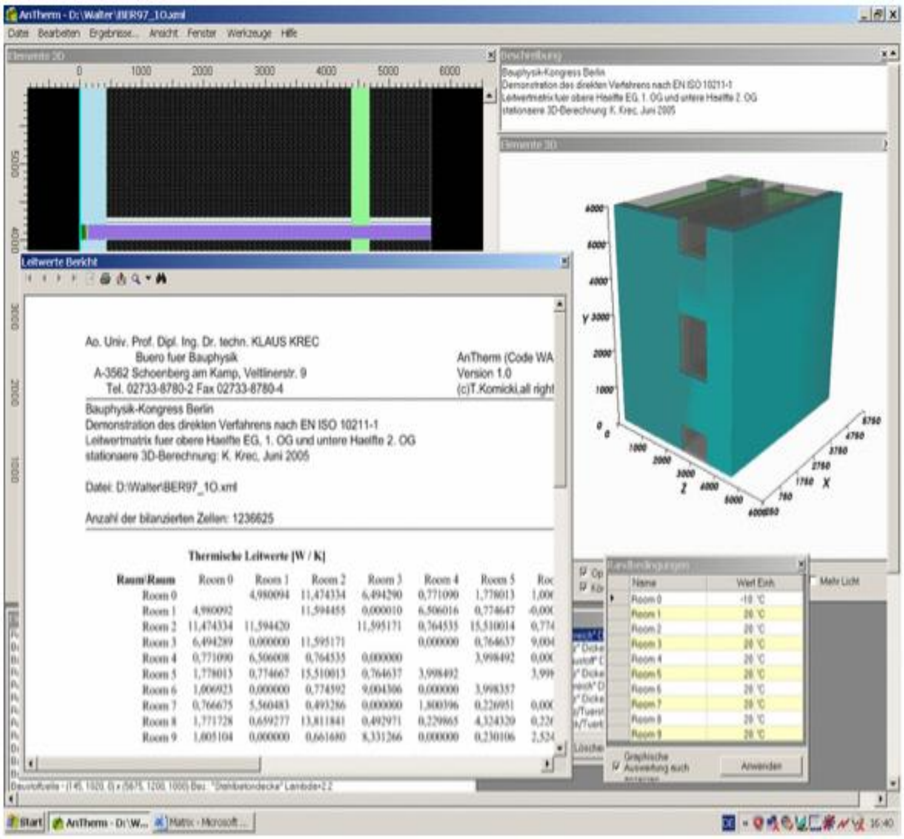


Figure 21. Sample screenshot of Antherm program. [41]

3.3.2.16 Delphin

Delphin is complete numerical simulation tool for moisture, heat and matter (e.g. salt) transmittance in porous building materials. Delphin is mostly applied to calculate transitory processes in construction details and building envelopes, also it predicates the condensation problem and durability. [**35**]

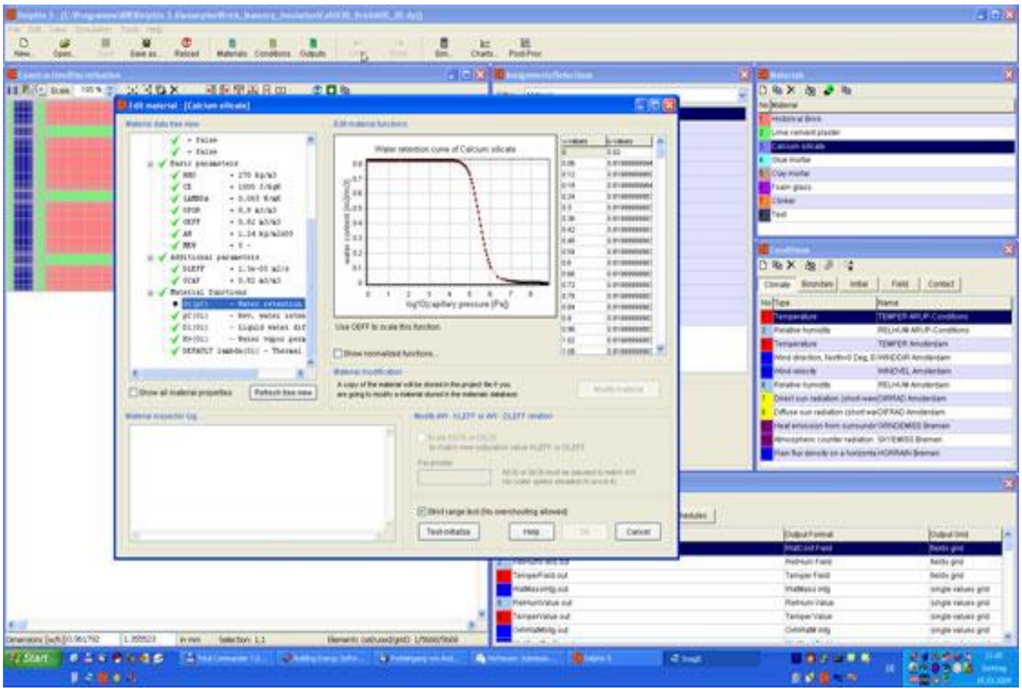


Figure 22. Sample screenshot of Delphin program. [42]

3.3.2.17 ECOTECT

3D modeling interface, complete environmental design tool with extensive solar, thermal, acoustic, lighting and cost analysis functions

This software provides visual and analytical feedback from sketch model and the result is completely scalable. It has simpler interface than EnergyPlus, Radiance and many other focused analysis tools. [**20**] [**36**] [**37**]

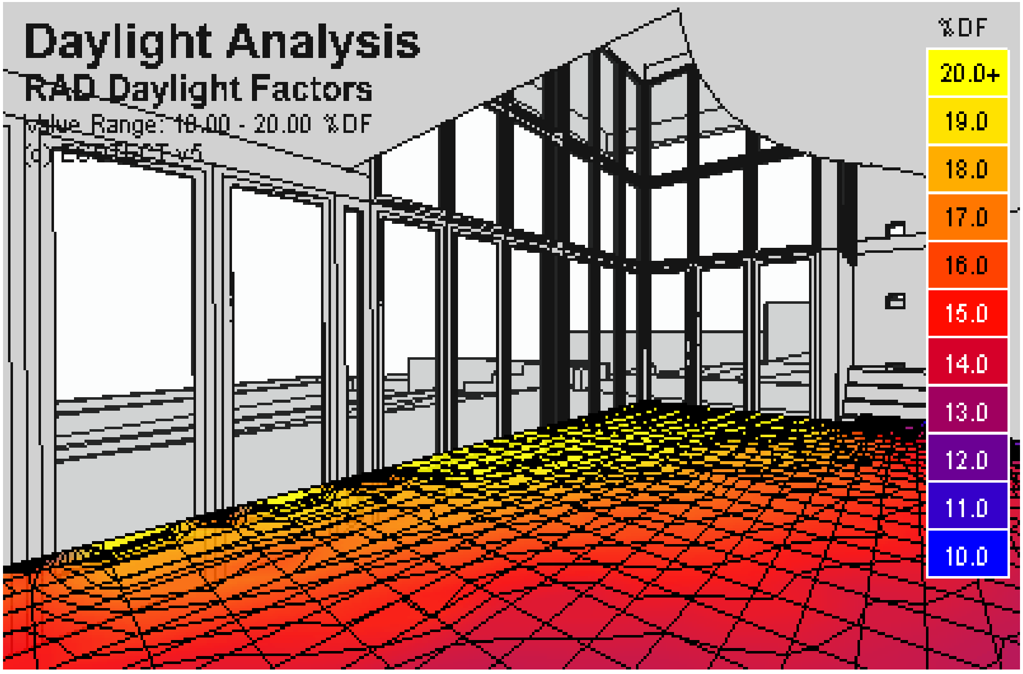


Figure 23. Sample screenshot of ECOTECT program. [44]

3.3.2.18 EnergyPlus

This software can calculate the ASCII output files in multi-zone airflow, electric power simulation (energy systems and fuel cells) and water manager systems (rainfall, ground water).

Energy plus is building energy simulation software that architects and engineers can use it to simulate the water and energy use in buildings. The optimization of energy and water can be done by modeling the performance of a building with energy plus.

Energy plus models cooling, lighting, heating, ventilation, water system and energy flows. It has capability of defining of time schedule, multizone airflow, ventilation, thermal comfort and photovoltaic systems. [**38**] [**20**] [**39**]

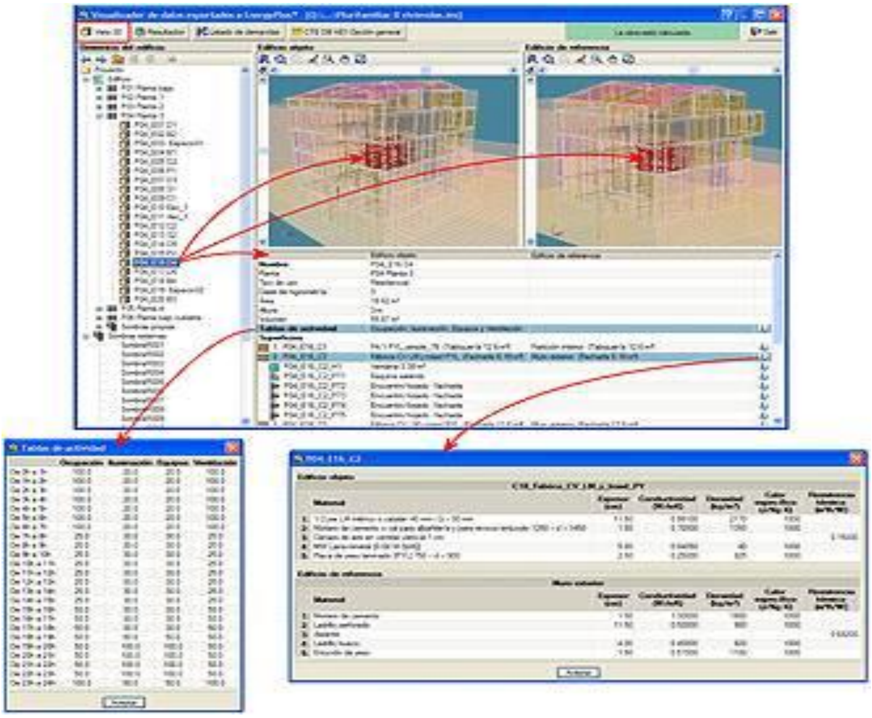


Figure 24. Sample screenshot of EnergyPlus program.[46]

3.3.2.19 eQUEST

This software provides interactive graphics, parametric analysis and fast execution for building simulation from conceptual step to final. [**20**] [**40**]

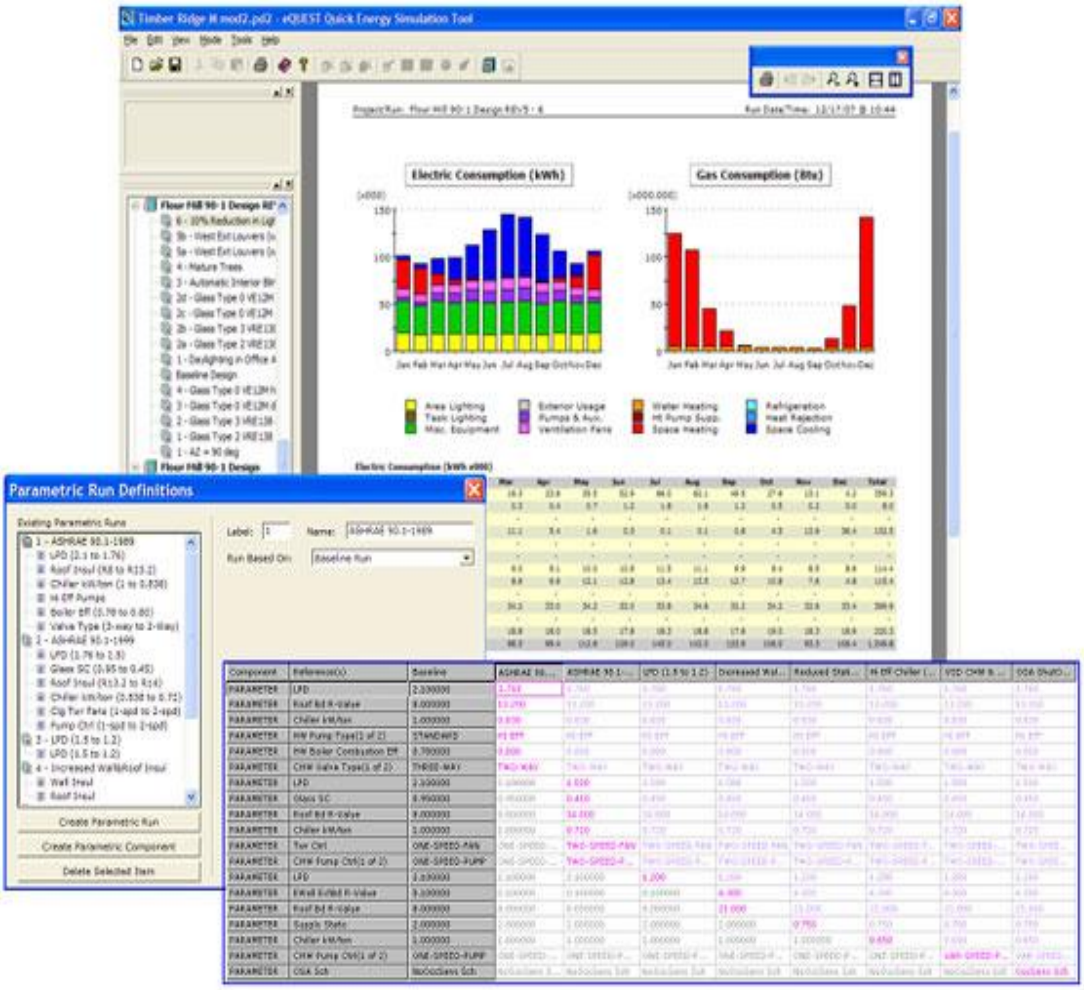


Figure 25.sample screenshot of eQUEST program. [**40**]

3.3.2.20 MOIST

Software that can predict transfer of heat and moisture in building with multi-layer construction, Using a diskette that contains hourly weather data as an input and prediction of moisture content and temperature of construction as an output. Mostly used in controlling moisture in walls, cathedral ceiling and flat roofs. [**21**] [**41**]

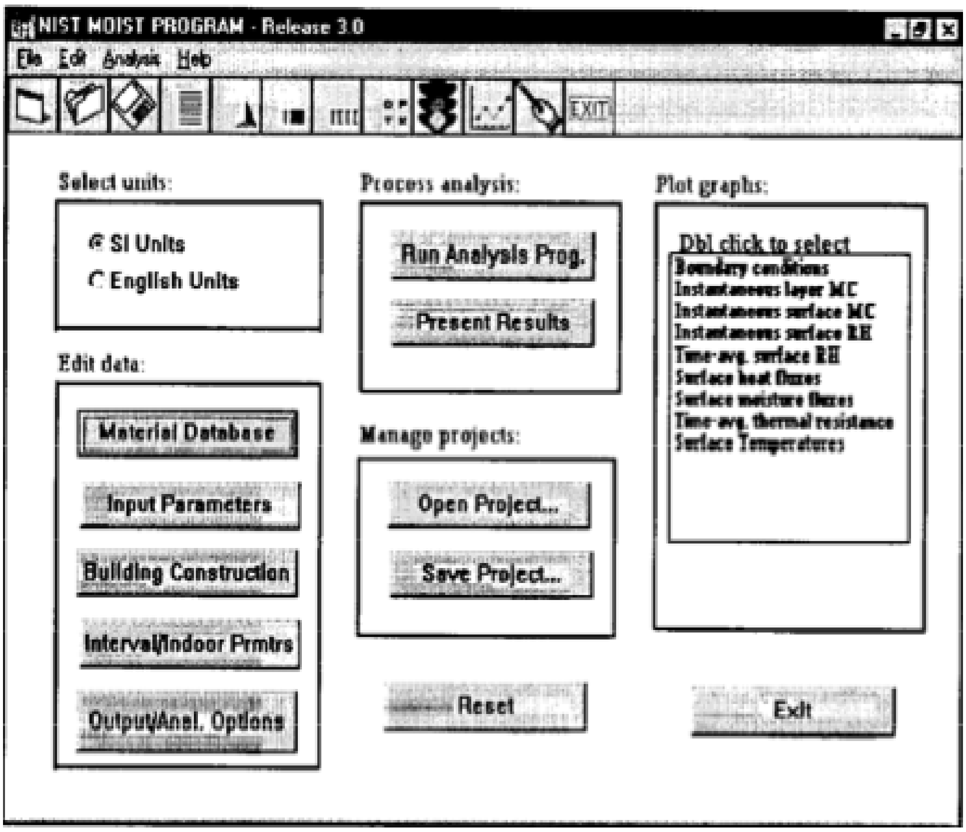


Figure 26.sample screenshot of MOIST program. [**41**]

3.3.2.21 PsyCalc

PsyCalc calculates temperature, moisture and pressure by using psychrometric method.

It returns ASHRAE (1997 chapter 26) the climate design information. PsyCalc software calculates airflow by built in airstream calculator upto 1 million cfm. PsyCalc is working with SI units and in English. PsyCalc has some other features such as saving, printing and use minimum screen space. [**42**]

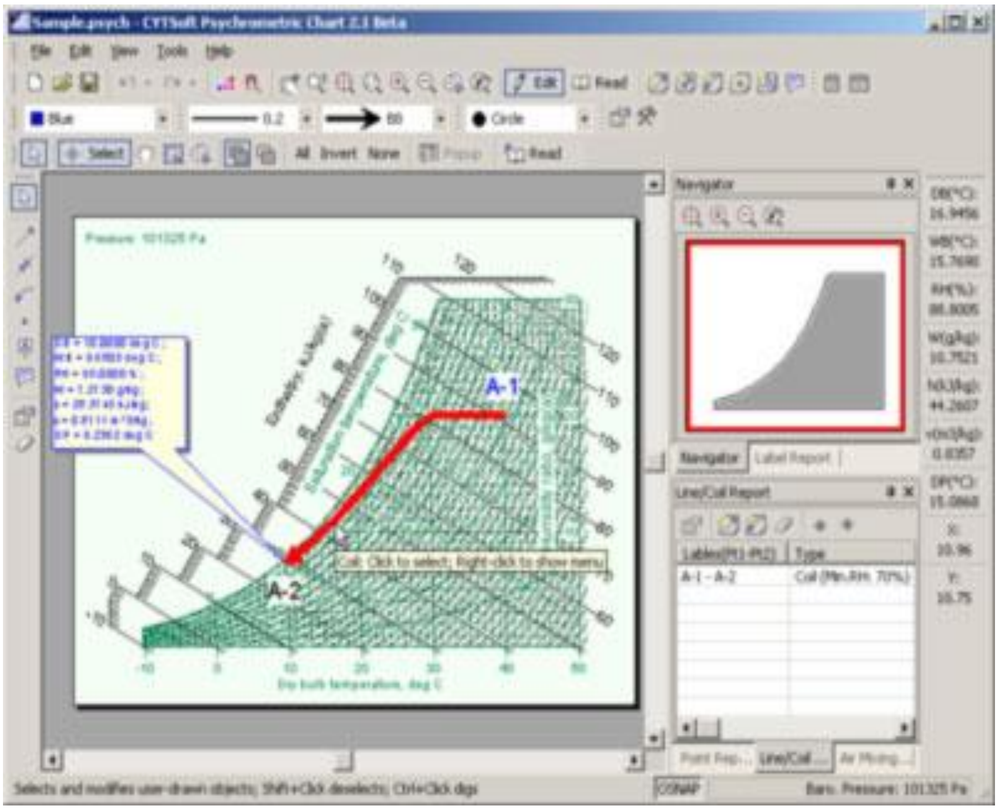


Figure27.sample screenshot of PsyCalc program. [**42**]

3.3.2.22 TAS

The TAS software, which is, provides thermal analysis of buildings. This software includes; systems or controls simulator, thermal and energy analysis for report and 3d modeller. TAS accepted AutoCAD input in its 3d modeller. Also it has a powerful design tool for the building environment optimization, energy and performance of comfort. [**20**]

Figure 28. sample screenshot of TAS program. [**43**]

3.3.2.23 Thermal Comfort

This software calculates and predicates the thermal comfort parameters by using several thermal comfort models. All calculations are based on equations, algorithms and models extracted from the literature (Fanger 1967, Gagge Fobelets Berglund 1986, Doherty Arens 1988, and Int-Hout 1990).

The Thermal Comfort software for a selected environment can predicates human response by using thermal comfort models such as PMV-PPD, ET*-DISC. Calculation of the predicated thermal comfort for the average hypothetical human in space can be done in this software. [**44**]

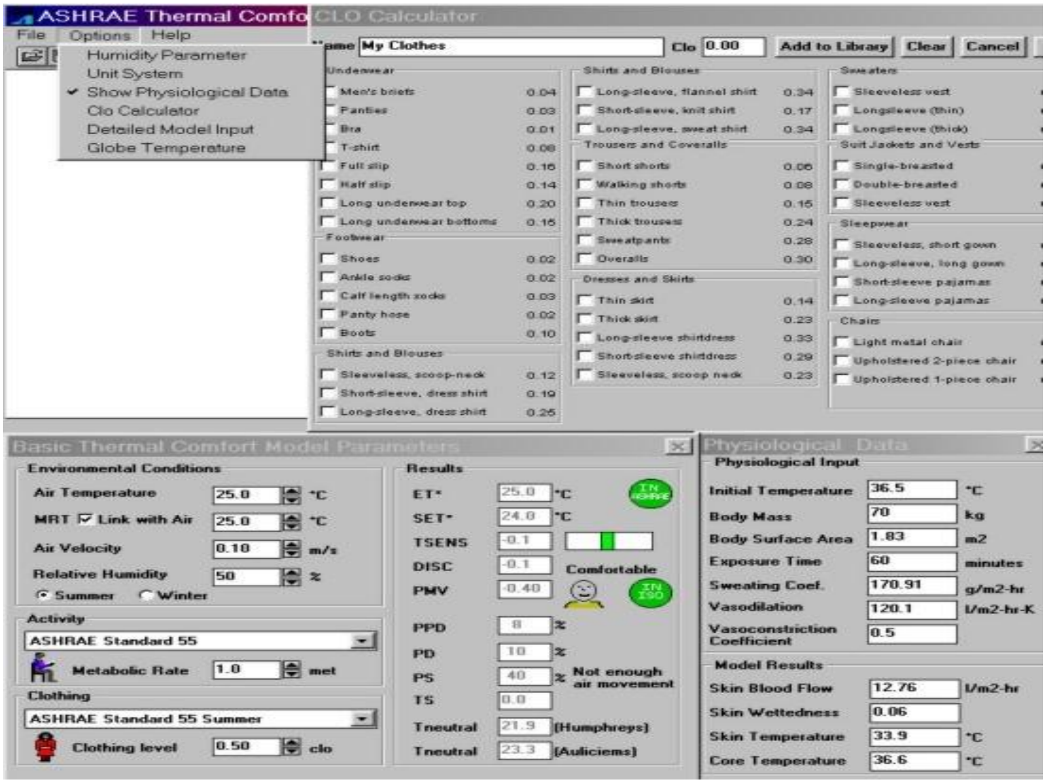


Figure 29. Sample screenshot of Thermal comfort program. [**44**]

3.3.2.24 TRACE Load 700

TRACE Load 700 can compute the effect of building size, orientation, shape, and mass based on hourly weather data and give the result for heat-transfer specification of air and moisture. This software uses ASHRAE recommended algorithms.

TRACE Load 700 has templates to provide an easy and fast way of analysis for effects of changes in building loads like thermostat setting, airflows, occupancy and construction. It has a wide library of construction materials, schedules, load generating source, shading types and weather profile of approximately 500 locations data entry. [**45**]

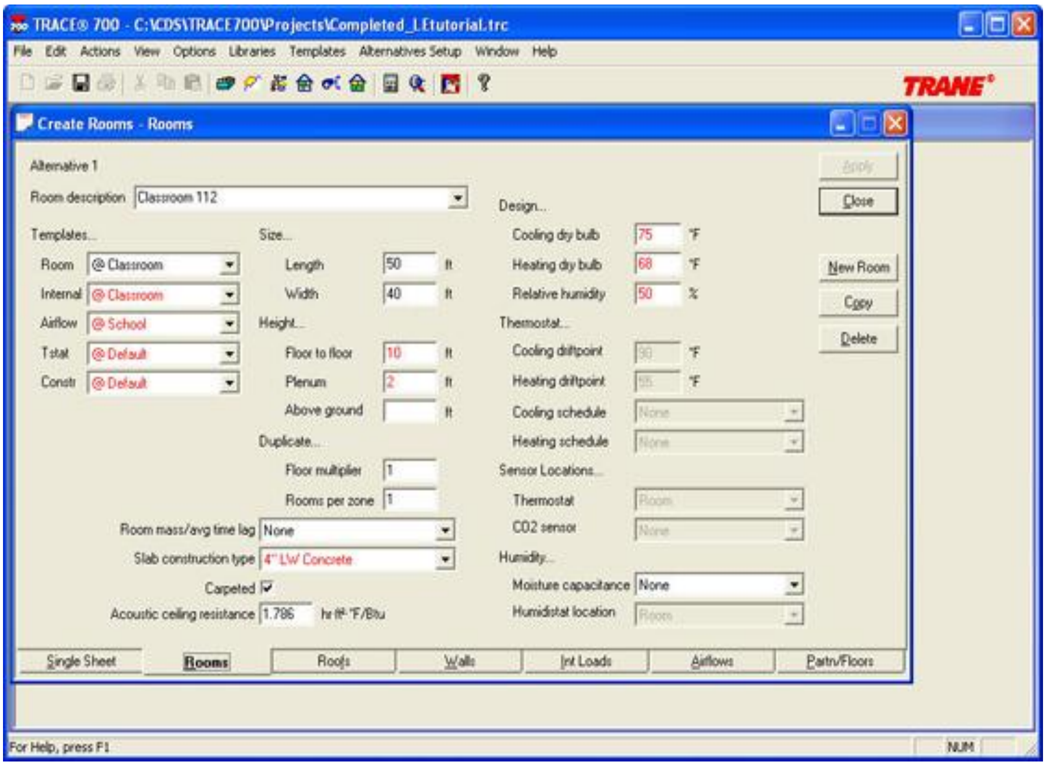


Figure 30. Sample screenshot of TRACE Load 700 program. [**45**]

3.3.2.25 WUFI-ORNL/IBP

WUFI-ORNL/IBP fixes the moisture transport and coupled heat in building envelope like roofs and walls by using hygrothermal model. This model is a combination of Oak Ridge National Laboratory and the Fraunhofer Institute in Building Physics (IBP). [**21**]

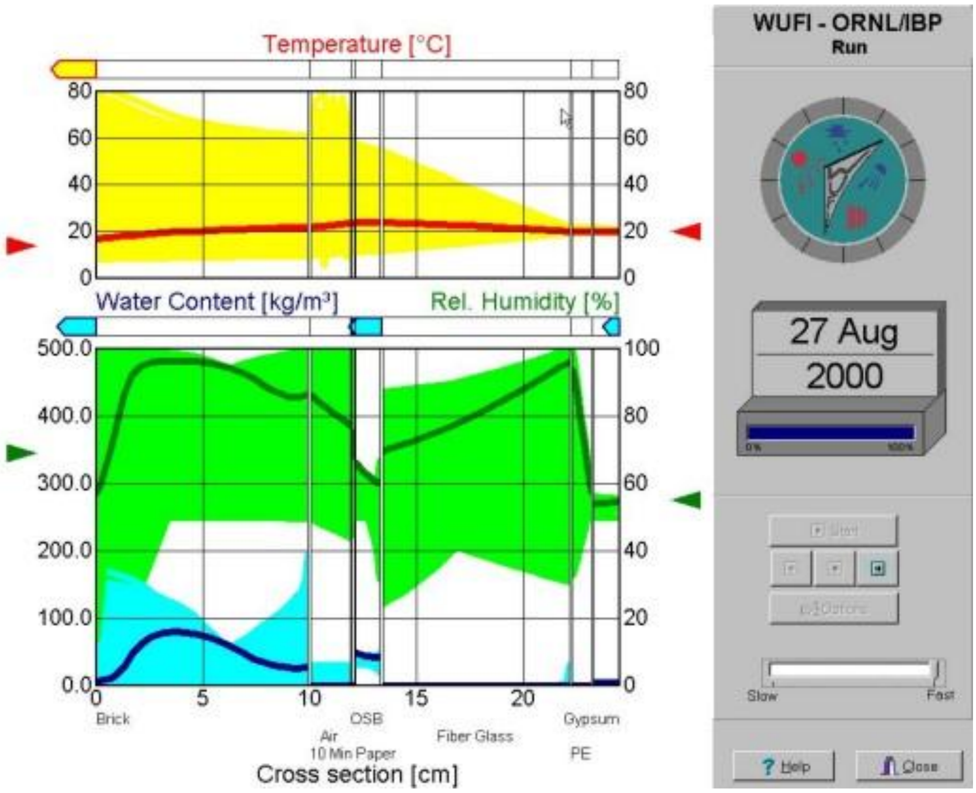


Figure 31.Sample screenshot of TWUFI-ORNL/IBP program. [**46**]

This software developed for architects and engineers by providing a good solution to moisture and damage assessment problems for building. [**46**]

Table 8.simulation program contact [**23**]

Programs	Contact
1D-HAM	http://www.buildingphysics.com
Moist	http://www.bfrl.nist.gov/863/moist.html
BSim	http://www.bsim.dk
Ecotect	http://www.squ1.com
ENERWIN	http://pages.suddenlink.net/enerwin
Energy plus	http://www.energyplus.gov
eQUEST	http://www.doe2.com
DOE-2	http://simulationresearch.lbl.gov
DeST	http://www.dest.com.cn
Psychart	http://www.coolit.co.za
Psycale	http://www.linric.com
HAMLab	http://archbps1.campus.tue.nl/bpswiki/index.php/Hamlab
FRAME 4	http://www.enermodal.com
Frame simulator	http://www.framesimulator.com
Design advisor	http://designadvisor.mit.edu
Delphin	http://www.bauklimatik-dresden.de/delphin/index.php?aLa=en
Antherm	http://antherm.kornicki.com/
WUFI-ORNL/IBP	http://web.ornl.gov/sci/btc/apps/moisture
VISION 4	http://www.enermodal.com
UMIDUS	http://www.pucpr.br/pesquisa/lst/
TRACE Load 700	http://www.trane.com/Commercial/Dna/View.aspx?i=1137
Thermal comfort	http://xp10.ashrae.org/bookstore/bookstore.html

Therm	http://windows.lbl.gov/software/therm/therm.html
PUTILITY Psychometric	http://gf.hvacsimulator.net
TAS	http://www.edsl.net/

3.4 Standards Used in Simulation Programs

a. -ASHRAE standard

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) ASHRAE began in 1894, with the purpose of giving minimum air quality percentages and ventilation that will be satisfactory to human occupants and inscribes determination of establishing harmony for method of standard practice, measurement or test and standard design. ASHRAE tries to reach the following goals:

- Reduce the energy consumption.
- Increase operational energy performance of buildings and facilities.
- Improve the mold and moisture instruments for building.
- Improve the ventilation methods while designing.
- Using less energy needed methods for dehumidification.

According to one of the researches which is done in United State (ATLANTA) in the title of energy consumption by reuse of air to make homes for low-income family units in humid and hot weather, they got: "The strategy is expected to provide substantial – over 50 percept – reduction in the overall HVAC&R energy consumption of residential buildings before any onsite energy reduction, according to the project, Partial Conditioning (Reuse of Air) as an Energy Saving Strategy for Sustainable Affordable Housing in Hot and Humid Climates."

ASHRAE standard is related with building simulation programs. Most of the simulation program confirm by ASHRAE and ISO standard. [**47**] [**48**] [**49**]

ANSI/ASHRAE standard 140-2001 method of test for evaluation of building energy analysis computer programs that is similarities many of tests in the first IEA BESTTEST which available from ASHRAE, for example ANSI/ASHRAE/IES Standard 90. 1-2007: Energy standard for buildings except low-rise residential building as the commercial building energy code in Ohio, ASHRAE 55-2010: Thermal environmental conditions for human occupancy and ANSI/ASHRAE/IES Standard 90. 2-2007: Energy-efficient design for low-rise residential buildings, ASHRAE125-1992 RA 2011: Method of rating unitary spot air conditioners, some simulation program like thermal comfort confirm with standards ASHRAE Standard 55 and ISO 7730, and etc. check the standards table for more information about standards and they related with methods. [**47**] [**49**] [**10**]

Table 9 has the most of ASHRAE standard codes related to moisture, ventilation for indoor air quality, building energy and HAVC.

Table 9. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard. [**47**] [**38**] [**48**] [**10**]

ASHRAE	**Title**
62.1-2010	“Ventilation for acceptable indoor air quality”
62.2-2010	“Ventilation and acceptable indoor air quality in low-rise residential buildings”
ANSI/ASHRAE/IES Standard 90.1	“For commercial building energy codes, is indispensable for those involved in the design of building and building systems.”

ANSI/ASHRAE/IES Standard 90.1-2010	“Energy standard for buildings except low-rise residential buildings”
ANSI/ASHRAE/IES Standard 90. 1-2007	“Energy standard for buildings except low-rise residential building as the commercial building energy code in Ohio.”
ANSI/ASHRAE/IES Standard 90. 2-2007	“Energy-efficient design for low-rise residential buildings”
70-2006 (RA 2011)	“Method of testing the performance of air outlets and air inlets.”
125-1992 (RA 2011)	“Method of testing thermal energy meters for liquid streams in HVAC systems.”
128-2011	“Method of rating unitary spot air conditioners.”
183-2007 (RA 2011)	“Peak cooling and heating load calculation in buildings except low-rise residential buildings.”
189. 1-2009	“Standard for design of high performance green building. ASHRAE conjunction with USGBC and IES in high performance green building.”
189. 2P	“For the design, construction and operation of sustainable high- performance health care facilities.”
55-2010	“Thermal environmental conditions for human occupancy”

Next table (table10) shows most related codes of ISO standard to building construction, thermal environmental, climate conditions and building environment design.

a. -ISO standard

This section provides the related ISO standards with the simulation programs. The following table describes the standard codes, which are used in the simulation software. [**50**]

Table 10. ISO standards on building construction (indoor) and (outdoor). PMV (Predicated Mean Vote), PPD (Predicated Percentage of Dissatisfied). [**50**] [**15**] [**9**]

ISO Standard	Title
ISO 6242-1:1992	“Building construction -- Expression of users' requirements -- Part 1: Thermal requirements”
ISO 15927-1:2003	“Hydrothermal performance of buildings—calculation and presentation of climatic data-- Part 1: Monthly means of single meteorological elements”
ISO/DTR 21932	“Building construction--sustainability in building construction – terminology “
ISO 6242-1:1992	“Building construction – Expression of users’ requirements -- Part 1: Thermal requirements”
ISO 6707-1:2004	“Building and civil engineering – vocabulary – Part 1: General terms”
ISO/DIS 11855-1	“Building environment design – Design, construction and operation of radiant heating and cooling systems – Part 1: Definition, symbols, and comfort criteria”
ISO 6242-2:1992	“Building construction – Expression of users’ requirements – Part 2: Air purity requirements”
ISO 7730	“Moderate thermal environmental – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort, (EN ISO 7730)”

ISO 7993	“Hot environments- Analytical determination and interpretation of thermal stress using calculation of required sweat rate”
ISO 7726	“Ergonomics of the thermal environment – Instruments for measuring physical quantities”
ISO 8996	“Ergonomics- Determination of metabolic heat production”
ISO 9920	“Estimation of the thermal insulation and evaporation resistance of a clothing ensemble”
CR 1752	“Ventilation for building – Design criteria for the indoor environment, CR 1752 is a technical report prepared by technical committee CEN/TC 156, ventilation for buildings.”

Chapter 3

EVALUATION OF THE MOISTURE MEASURMENT, PREDICTION AND SIMULATION METHODS IN BUILDINGS

As one of the major aims of this thesis, we investigated the outcome of various techniques of moisture detection and measurement including geographical, mechanical and simulation methods. Each method has its own pro, cons and trade-offs that are indicated in the content of this research. Therefore, the recorded results and comparison tables can be of great help to architects to choose the most appropriate approach to discover and resolve moisture related problems in building.

4.1 Evaluation of Measurement Methods

Choosing a correct moisture measurement method can play a critical role to save time, money and resources in the project and most importantly can improve the quality of the outcome in the projects. Simulation and graphical method is a great method enabling prediction and control of moisture content before construction operations while mechanical method is designed as post-construction technique on the structure of buildings and materials. Measuring moisture content before and after construction is compulsory for durability and energy saving.

Available Tools developed for mechanical method are designed to use, moisture measurement in different locations of the buildings and structures as input and analyse the provided information. Depending on the material and location of the structure, selection of method and tool would be different. For example if the structure is a bridge, measuring the moisture by handheld pin type measurement tools can be a labour intensive operation because the moisture spread all over the structure in a non – uniform basis, whereas having a tool that has an ability to screen a bigger area of structure is of more convenience and in some cases increases the accuracy f the measurement.

Microwave and infrared technologies enabling user to scan a larger surface of the building by spending less time and energy while adding more accuracy. Meanwhile the resistance method is influenced by many factors such as physical contact which is essential in this method can be a major problem. Furthermore resistance method cannot give accurate result if the moisture level is less than 7% and more than 23% [**6**].

The other popular method is "capacitance" which has fewer mistakes in computation results when compared to resistance. Capacitance method gives accuracy within ±1%, which is primarily applicable in agriculture. [**6**] [**6**]

This section provides comprehensive comparisons between different methods that are mentioned in this thesis viewing each method form architectural perspective. Comparisons are mainly focus on the methods in which can give best result in terms of prediction and calculation of moisture level in building from an architect perspective. In these comparison methods have chosen based on their efficiency and available tools to get the best result in accuracy, maintenance and cost. Thereafter, the results of each experiment are compared with the outcome of researches recorded my other experts.

-Comparison of mechanical methods to moisture prediction

In the resistance and voltage based method the amount of electricity that is passed through the pins or sensor is computed. When the wetness of surface or material is large the electrical resistance is low. In the thermal based method the changes in temperature of the material caused by the amount of moisture is measured. This method is using special type of sensor to compute the temperature of material in different levels. The other technique known as microwave, infrared is the most practical technique in terms of accuracy, durability and usage; with the penalty of more cost.

The next table comprises some other features like usage, durability, etc. of methods.

Table 11.Summaries of mechanical methods and tools [**6**]

Method	**Tool**	**Usage**	**Accuracy**	**Durability**	**Maintenance**	**Mobility & Tool Price**
Resistance Based (e.g. moisture pins)	With Pins (can be ceramic or steel…)	Woodworking, building construction	(±) 2% (Grahan 1988)	Good	Less	Portable device Starting at ≈50$
Voltage Based (e.g. sereda)	With pins (can be a electrochemical sensor or copper)	Woodworking, building construction, and agriculture	±1% [**6**]	Medium comparing to resistance base method	Medium	Portable device Starting at ≈ 50$
Thermal Based (e.g.	Pin or pin less (depends on	Woodworking, building	±1% [**6**]	Almost	Almost	Portable & non-

heat sink)	the method like heat sink or thermal conductivity)	construction, and Bridge construction		permanent	none	portable device Starting at ≈ 50$
Diagnostic Method (e.g. microwave, infrared)	Pin-less (Electromagnetic or infrared)	Woodworking, building construction, Bridge construction and agriculture	Good accuracy (Dill 2000)	Medium	Medium	Portable $ non-portable device Starting at ≈ 300$

Note for table: Maintenance of materials used in tools (e.g. resistance-based tools has less maintenance of voltage based tools.

Notes for table: The Durability and Maintenance columns are comparing sensors with each other.

4.2 Evaluation of Prediction Methods of Moisture in Buildings

Before the construction of a building predicating the moisture in the whole building can be done with graphical and simulation methods. Simulation method is more useful than graphical method because of the powerfulness software that considers all conditions before the construction. Simulation software are more convenient to use with architects while in most of the programs the AutoCAD files can be imported.

The graphical method is a simple mathematical calculation that can predicate moisture in building before construction by simply computing some factors like thickness of material and water permeability. The simplicity and less costly of graphical method are its advantages than simulation software.

4.3 Evaluation of Moisture Simulation Methods in Buildings

Generally, Simulation tools are reliable and trustworthy computer programs that are used to predict the condensation, along with building energy simulation and many other incredible features, these application are deployed in different computer language platforms, which get some data form an expert (architecture, civil engineer) as inputs and simulate outputs dependent on the user request in interior and exterior construction of a building.

Inputs and outputs are vary in different program, but popular outputs are basically; moisture content, temperature, relative humidity's, indoor thermal environment, energy balance of building components, peak loads, life cycle cost, HVAC system, heat flow, condensation risk which determines the characteristics of a building. The 24 moisture related simulation software are introduced and defined in chapter 2 are however in this chapter, table 13,20 provides an informative comparison between 11 of them, which are specifically deployed for moisture. These 11 simulation programs have been selected according to their relation to moisture, standards used and audience types, however they are all using the same for and data analysis and mainly targeted for architectural audience.

Pre and post construction moisture control of the buildings should be considered are a principle which can be achieved using available tools, which are designed with the existing standards to satisfy the need of sustainable and green buildings this section described and compares four standards that are related to moisture control in buildings.

4.3.1 Simulation software general features

Table 12, demonstrates a detailed comparison between different simulation software considering general features such as target users, audience, price, weakness, validation and the used standard are compared. In this comparison some factors that are more related to architectural affairs and have the minimal vulnerabilities and weaknesses with confirmed validity have been chosen.

4.3.2 Input Data of the Simulations

a. - General features

Table 13 shows all input data that each software needs to obtain the desired result (output). These information are about the building geometry, geographic, Daylight control, Building materials some information about the interior and exterior characteristics and some of them demand information about electric and other utilities.

Table 14 is also about the software inputs but a generic category of data entries including climate information that software requires as part of the algorithm like ventilation, thermal zone and etc., these all are categorized as “general climate data”

b. -Modelling Format

Table 15 shows the input data formats compatible with each software. Some of them are getting the input by AutoCAD (WDG file) some demand for text or script based files and some require ASCII. However many software have their own proprietary designing tools to create hypothetic buildings and use them as simulation inputs.

4.3.3 Output Data of the Simulations

a. -General features

Table 16 is about comparing Moisture content, Indoor Temperature, Thermal simulation; Energy balance, Lighting balance, and Construction material etc. These are particular result that each program supplies as result of analysis and simulation the given input data.

b. -Modelling Format

Table 17 shows the selective output data formats. These formats can be in, Graphs, Texts, 2D.

c. -Periodical Report

In table 18 comprises of scheduling report frequency, which automates the generation of hourly, daily, weekly or annually reports in any of the mentioned output formats mentioned the table 17, nevertheless some software which doesn’t t have comprehensive documentation doesn’t t have proper explanation of this critical feature or in worse case some of the software don t support this feature at all.

d. -Format

Output formats mention din table 19 can be executed in one of the programs shown in table 20 offering the ability to view the simulation results in animation, AutoCAD DXF, ASCLL, Image file, PDF. Detailed explanation of each table item is could be found after corresponding table. Each program is a reliable evaluation source and insurance for sustainable, green and healthy built and is just dependent on the situation of building design process, the location and environmental condition of land.

Table 12: Simulation software feature

Simulation software feature	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
User	Over 150	Over 25000	Over 2000	Over 85000	Over 9.000	Over 1250	Over 6000	Over 250	Worldwide distribution	Over 2100	Over680
Audience	Architectural engineers Student, Universities and research laboratories. Building designer. Energy Consultants.	Architectural engineers. Student, Universities and research laboratories. Building designer.	Architects, engineers, environmental consultants, building designers	Architectural engineers working for architect/engineer firms, consulting firms, research universities, and research laboratories.	Architectural engineers. Consulting firms. Student, Universities and research laboratories. Building designer. Energy Consultants.	Architectural engineers. Consulting firm, Architectect	Architectural engineers	Architectect Student, Universities and research laboratories. Building services engineer.	Architectural engineers. Student, Universities and research laboratories	Architectural engineers	Architectural engineers. Consulting firms. Student, Universities and research laboratories. Building designer.
Price	560 euro to 5000 euro	Free for students, small fee for academic	US$75	$300	FREE	FREE	$49.95	£1600	$117	$695	FREE
Validation/testing	Validated to conform all 4 cases of EN ISO 10211:2007, Annex A, for three-dimensional calculation programs.	Validated to conform to both two-dimensional cases of ISO 10211:2007, Annex.	Partially implemented (e.g. it addresses part of an issue, does not yet fully represent the underlying physics or is a work-in-progress)	Tested against the IEA Besets building load and HVAC tests Henninger and Witte (2004a)	Tested according to ASHRAE Standard 140.	Tested according to NIST	N/A	Tested according to ASHRAE Standard 140-1	N/A	Tested according to ASHRAE Standard 140.	N/A

Weakness	For three dimensions graphical needs large memory and high CPU speed.	Complex in interaction of different models. Transport process requires much experience.	Unsuitable for not expert user	Text input may make it more difficult to use than graphical interfaces.	not support SI units. Infiltration/natural and Ground-coupling ventilation models are limited.	Support only one-dimensional, no result for moisture transfer and heat is air movement.	Not mentioned.	Not intended for detailed services layout design.	Some ASHRAE standard 55 that are not addressed in this program. Is not a design tool for determining thermal sensation in any specific building?	Needs TRACE 700 to obtain cost and energy analyses Complex format for new users.	support only one-dimensional, no result for moisture transfer and heat be air movement.
Based on	EN, EN-ISO	EN, EN-ISO	NIST	ANSI/ASHRAE 140(2007)	ASHRAE 140	NIST	ASHRAE	ASHRAE	ASHRAE 55 ISO 7730	ASHRAE	ASHRAE 160P

This table shows the

- Popularity of each software
- The audience that may interest in using the software
- The price
- Testing organization that is validated the software
- Some weakness that are founded by expert users
- The standards that are used in software

And in this table Delphin, EnergyPlus, and eQUEST, have more users in comparison to any other programs and the validation and testing are well standardized based on well-known standarrds such as ISO and ASHRAE,

Table 13: Input building characteristics in simulations programs

Input building characteristics	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
Building geographic location	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Building geometric characteristics	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Building orientation	✓	✓				✓	✓	✓	✓	✓	✓
Building materials	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Building equipment			✓	✓				✓			✓
Daylight control	✓		✓	✓	✓			✓	✓		
Building operation			✓	✓			✓			✓	✓
Electric utility characteristics		✓	✓		✓			✓		✓	✓
Interior characteristic	✓		✓		✓	✓		✓			✓
Exterior characteristic	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Building geometric: building area, Building geography: e.g. location of country.

Building orientation: north or west faced building.

Building material: wall, cathedral ceiling, or low-slope roof, metal, wood, concrete etc.

Building utilities: e.g. HVAC.

Building operation: typical use, low use, and high use.

Interior characteristic: door type, Glass, air lock entry, windows type, light.

Exterior characteristic: lighting, weather climate. In the above mentioned simulation programs most of the important characteristics such as building geometry, building geography, building material can be given to program as input but depending on the it's design some of them are

Getting the input only form their own graphical interface, some are compatible with .DWG files format and others accept wide variety of the input file formats.

Table 14: Input General Climate

Input general climate	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
Ventilation characteristics					✓						✓
Climate data	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Thermal zone characteristics	✓					✓					✓

Climate data: air temperatures and weather data that include rain, wind …etc. to analyze the building energy uses.

Ventilation characteristic: ventilation system airflow rates, and whole house air change rates under different ventilation configurations and weather conditions

Thermal properties of materials: conductance properties of materials, transfer coefficient of surface elements (standard properties available by selection from the material database included).

Table 15: Input Modeling Format Files

Input modeling format files	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
AutoCAD formats file (e.g. DXF)	✓	✓	✓	✓	✓	✓		✓			✓
AutoCAD file (3D)	✓	✓	✓	✓				✓	✓	✓	✓
Graphical editor interface with CAD functionality	✓	✓	✓				✓	✓			✓
Drawing sketch interface		✓		✓	✓	✓					✓
Text file	✓	✓	✓		✓	✓	✓	✓			✓
ASCII file				✓				✓	✓		

Within the above mentioned simulation programs Antherm, Delphin, ECOTECT, EnergyPlus, TAS, Thermal comfort, TRACE Load 700, and WUFI have 3D, and they are convenient for analysis purposes . Graphical editor interface with CAD functionality, and Drawing sketch interface are the features rendering these programs clear cut and neat to use.

Table 16: Output General Feature

Output general feature	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
Moisture content	✓	✓				✓	✓			✓	✓
Indoor Temperature	✓	✓		✓			✓			✓	✓
Thermal simulation		✓	✓					✓	✓		✓
Energy balance				✓	✓			✓	✓	✓	✓
HVAC system				✓	✓		✓	✓	✓	✓	✓
Ventilation	✓	✓	✓	✓		✓		✓	✓	✓	✓
Heat balance	✓	✓		✓	✓	✓				✓	✓
Lighting balance	✓		✓	✓	✓			✓			
Construction material	✓	✓			✓						✓

Moisture content: in practice moisture in any surface, including relative humidity and condensed humidity, surface condensation, interstitial condensation is called moisture content. Define wall, cathedral ceiling, and low-slop roof construction. Parameter on the moisture accumulation within layers of the construction. Controlling moisture in pain layers, wallpapers, and vapour retarders

Indoor temperature: this includes internal indoor distribution of temperature, heat streams, vapour diffusion streams, and vapour pressure in component interior.

Thermal simulation: the state of mind that expresses satisfaction with the surrounding environment (ANSI/ASHRAE Standard 55[1]), and calculation of thermal bridges, dynamic thermal simulation, and thermal analysis.

Energy Balance: cooling and heating loadswhich is dependent on design, orientation, material and geometry, and energy consumption should be calculated precisely. .

HVAC system: Heating, Ventilation and Air conditioning refers to technology of indoor or automotive environmental comfort. HVAC modules (coils, boilers, chiller, pumps, fans, and other equipment or component), infiltration and ventilation, coolingand heating supply air temperatures, should also be considered.

Ventilation: Airflow. Heat balance: the flows of heat conduction and air across the internal surfaces of walls, roofs and floors that enclose that space.

Construction material: Construction and Material development and optimization, building type and size, floor plan

Table 17: Output Modelling Format

Output modeling format	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
Chart		✓	✓	✓		✓		✓	✓	✓	
Graph	✓		✓	✓	✓	✓		✓			✓
Text	✓	✓	✓		✓	✓	✓	✓	✓	✓	
Table				✓	✓	✓				✓	
2D	✓										
3D	✓		✓	✓				✓			

Note: Note: This table illustrates the output format, These formats are categorized as Chart, Graph, Text, and 2D .

Table 18: Output Periodical Report

Output (information) periodical report	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
Hourly	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Weekly			✓	✓	✓			✓			✓
Monthly	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Annually	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Note: The output information periodical report shows each simulation programs output report time schedule result.

Table 19: Output Format Files

Output format files	Antherm	Delphin	ECOTECT	Energyplus	eQUEST	Moist	PsyCalc	TAS	Thermal comfort	TRACE Load 700	WUFI-ORNL/IBP
Animation											✓
AutoCAD DXF	✓		✓	✓	✓			✓			
ASCII			✓	✓		✓			✓	✓	
Image file	✓	✓	✓	✓	✓	✓		✓		✓	
Binary		✓									
PDF	✓				✓						
XML			✓				✓				
Excel and Word			✓	✓			✓	✓	✓	✓	

Output format files: Antherm program support wide variety of file formats including XLS, OOGL (3D graphic), OVI, VRML, RTF and also Image file: JPG, BMP, PNG

4.4 Overall Evaluation of Moisture Effect on Building by using measurement, prediction and simulation

In this section provides comparison methods and determines the best method to be used during different steps of the project.

4.4.1 Evaluation of the Building in terms of moisture effects in Design Stage

In design stage we should predict the moisture content, which may occur during or after construction, is. Selection of an appropriate method is dependent on several factors including geographical location, material quality, climate; geometric characteristic, and thermal conditions. The desirable outcome of the simulations would be probability and percentage of moisture content, which would appear after the construction. Selection of an appropriate method in design can diminish the impact of the mentioned issues on a building. These methods are simulation software and graphical methods, which can predict the amount of moisture with collected facts about the pseudo building. In the following section methods for prediction of condensation risk in a building component during the design will be explained.

4.4.1.1 Prediction of Condensation Risks of Building Components

As mentioned before in previous chapters, the condensation may yield serious damages to a building wall, surfaces, ceiling and floor. The condensation appears for different reasons such as: pressure differentials, External Solar radiations, and interstitial condensation. Predicting the probability of condensation before and after the construction is critical step to reduce the amount of moisture and water leakage in building. By choosing an adequate simulation software tool with proper options in terms of condensation predication, the chance of condensation can be reduced quiet dramatically.

In the following section we firstly describe the usability of simulation software in prediction of condensation. Then the applications of graphical methods will be shown with their limitations and constrains.

A - Using simulation software

There is not only one optimal software package that can completely fulfil all users' requirements. Each program focuses on an specific part of required outcomes. For instance EnergyPlus and TAS have more options on HVAC systems (air loop, air distribution systems, information about heating and cooling systems, and etc.) and ventilation (wind calculation, natural ventilation calculation, and air flow zones.). This is because of significant effect of HVAC and ventilation on condensation issues.

Following sections provide detailed information about these software.

Table 20: two simulation programs that have HVAC system and Ventilation system in their information.

Energy Plus	**TAS**
For HVAC systems 1. Idealize HVAC systems 2. Air distribution system 3. Coils information	For HVAC system 1. Coils information 2. Air loops, outside air, zone air flow 3. Humidity control
For ventilation 1. Automatic calculation of wind pressure 2. Infiltration	For Ventilation 1.Infiltration 2.automatic calculation of wind pressure 3.natural ventilation 4. Windows positioning for natural ventilation 5. Multi zone airflow 6. Mechanical ventilation

B – using graphical methods

The two illustrated manual design tools method (Glaser and Dew point) in chapter 2 are used for determining the condensation of building envelopes (roofs, ceilings, and walls). Both methods compare vapor pressure inside the envelope by computing the vapor diffusion equation, with pressures of saturation in terms of temperature inside the envelope. This calculation identifies if condensation occurred within any point of the envelope by checking whether vapor pressure is above the saturation or not.

The Dew point uses water vapor permeability within envelope while the Glaser uses diffusion coefficient of water in the air and diffusion resistance factor of the material to find out the condensation. The differences between Dew point and Glaser are between their formulas and the graphical procedure; also Dew point is used in America and Glaser in Europe and in other places. [**19**]

Both methods have the following limitation according to EN ISO 13788 (2002) and TenWolde (2001)

1) Thermal conductivity not dependent on moisture and ice content in the material.

2) Water vapour permeability not dependent on relative humidity (moisture content).

3) All moisture mechanisms other than vapour diffusion are excluded.

4) Moisture storage in the building materials is neglected.

5) Movement of air through materials or in cavities is neglected.

6) Rain precipitation or snow is not taken in to account.

7) Methods are steady-stated and do not take into account transient boundary conditions.

8) Transport of water vapour through the materials is only one-dimensional.

9) Short and long-way radiation is neglected.

10) Latent heat from evaporation/condensation is neglected.

Because of the above limitations these methods are used as a guess result for the condensation and they are usually suitable for comparison of building structure, because they are not exact description of moisture behaviour inside structure. so in practice usually simulation method is used.

4.4.1.2 Prediction of Moisture Movement in Building Construction-Moisture, Water Content and Draying

Moisture content and water vapor will tend to go around form the places with higher vapor pressure to the places with lower vapor pressure. For example, some location in the house like bathroom that has more humidity, the moisture content tends to spread to other surfaces near the bathroom. Great care should be taken in the design of buildings to ensure that warm moist air cannot move from local major sources of water vapour, such as a bathroom, into other areas which have not been designed to take care of that much moisture content. Attention should be given to the ventilation, and HVAC systems to be designed in the best manner. Any mechanical ventilation systems should be designed to draw air from the rest of the building through the moisture generating areas to the outside. So prediction and selection of the good material and insulation techniques can be helpful to make a durable building. Simulation and design tools such as EnergyPlus, WUFI and TAS have special options and tools to provide special information to find out the moisture movement in building. The following table, compares three simulation software which are giving better information about the building material, material absorption, insulation of walls, windows, ceiling, floor; vapor pressure and so forth.

Table 21: information of Three simulation program as example .

EnergyPlus	**WUFI**	**TAS**
1.Description of walls, doors, roofs, floors	1. Description of walls, doors, roofs, floors	1. Description of walls, doors, roofs, floors
2. Description of windows, skylight and external shading	2. Description of windows, skylight and external shading	2. Description of windows, skylight and external shading
3. Heat balance calculation	3. Heat balance calculation	3. Heat balance calculation
4. Moisture absorption/desorption of material	4. Interior surface convection	4. Moisture absorption/desorption of material
5.Dew point temperature or relative humidity	5. Outside surface convection	5. Interior surface convection
6. Complete solar analysis 7. Complete insolation analysis		6.Dew point temperature or relative humidity
		7. Complete solar analysis
8. Outside surface convection		

4.4.2 Evaluation of the building in terms of moisture effects in Existing Building

Problems such as Bowing and buckling, wall cracks, condensation, stain, mold, softening of interior surfacing material, standing water in ducts and etc. are happening while the content of moisture increases in the building.

The mechanical, numerical calculations and graphical techniques are used for prediction and calculation the amount of moisture after building construction. After the prediction and gathering the information of the moisture content the growth of moisture can be controlled and avoided.

4.4.2.1 Prediction and Calculation of Water Leakage in Building Construction using mechanical tools

After the construction of a building is finished some problems to the water insulation, condensation from the pipes, malfunctioning of the water, heating and cooling systems are causing the water leakage and condensation in the existing building. Condensation and water leakage should be controlled and dried.

4.4.2.2 Condensation and water leakage avoidance in the existing building

The following terms can be obtained to control the moisture content and condensation in existing building:

a) Reduce the moisture input to the building by better insulation of doors and walls and etc.

b) Design better ventilation to get more vapor pressures.

c) Usage of better material that has more resistance to vapor in places that has warmer surface and vice versa. This is useful to get lower condensation.

d) Heat can reduce the amount of moisture.

e) Thermal resistance of the material is important in condensation. Material with low resistance should take place in side of the hotter surfaces and vice versa.

The above terms are used to get rid of moisture and condensation in a building after construction. Other than these rules the prediction of the condensation and water leakage is important. The mechanical methods are suggested to take care of condensation and water leakage in existing building.

4.4.2.3 Usage of methods in condensation and water leakage prediction

As it is mentioned in chapter 2 mechanical techniques are categorized to resistance, voltage, microwave and thermal functions. Remarks that in resistance and voltage based method the amount of electricity that is passed through the pins or sensor is computed. The other technique – microwave, infrared – is the most useful technique in terms of accuracy, durability and usage; but it is costly. Devices that are used in mechanical mainly divided into pin and pin – less types. The pin type computes moisture with pins that are pushed into the material in order to read the amount of moisture.

Deciding about the selection of appropriate tool is important to get the best accurate result. For example if the water leakage is happening in an hard to reach area like ducts the Infrared or microwave tools are preferable to use instead of pin type tools.

a) Suggested sensors for detecting water leakage

The following sensors can be used as a water leakage detector by considering the wetness of the surface that the sensors are installed. When the amount of moisture is increased rapidly that can be the reason of condensation or water leakage around the sensor.

i) Simple steel pin sensor (resistance based) that is used to define the wetness of material by passing the electricity from one pin to another.

ii) Serada moisture sensor (voltage based) can be used to compute the time of wetness and drying of the surfaces by placing the sensor at different location of the building façade. This sensor is fast enough to identifying the wetness of the surface. Also the ASTM approved the application of this sensor.

iii) Printed circuit sensor (voltage based) can be used to predicate and calculate the amount of moisture for less than 6 months usage. Because after 6 month the copper material that is used in the sensor is unusable.

iv) Heat sink sensor (thermal based) to determine the amount of moisture by finding out the temperature of the material.

v) Microwave based sensor that some of them can take the moisture content 25 times per second of the material that is located in front of the device.

vi) Infrared moisture sensor is used to take the thermal changes in the building to measure the amount of moisture in the building.

The similarity, pros and cons are compared as follows:

b) Similarity of sensors that are used for detecting the water leakage and condensation

All of the above sensors are usable for long run of the moisture measurement in a building but the time of the maintenance is varies in different sensor, like the 'printed circuit' sensor that goes about 6 months for each run. Sensors that can be installed inside the building materials (for steel pins, serada, printed circuit) or take place somewhere to catch moisture of a surface of the building (Infrared or microwave) depend on the request of architecture the result can be obtained hourly, daily or yearly. All tools are returning the relative humidity of material or the water content inside the material.

C) Comparing of advantages and disadvantages of sensors that are used for detecting the water leakage and condensation

Infrared and microwave sensors are preferable to use for architects; because, theses sensors are giving a chance to measure wider area of the surface or building in each calculation.

In terms of the destructivity or non-destructivity of material the microwave and infrared would be useful. For example buildings that are constructed with wooden elements, the non-destructive moisture sensors are more preferable. On the other hand, some buildings with the concrete or other hard materials, or any other cheaper in terms of price are preferable.

Microwave sensors also can identify much deeper moisture content of a surface that is one important issue for architecture to estimate and decide about the drying of the surface.

Steel pin sensors are causing some damage to material and surface because; they should be drilled into the material (this is the main drawback of steel pin type sensors, other one is that each device is connected to the pins by wire which can be twisted or tangled which causes accuracy to get low).

Figure (32) shows the way of measuring the moisture content inside the wall by removing some stone and cladding of the wall. This is the way that probe type sensors can determine the moisture content, so this is an obvious drawback of this method in calculation of moisture in building. Also measuring the amount of moisture for some locations in building or structures like bridges and high-rise buildings; it is more comfortable to use microwave or infrared. On the other hand computing the amount of moisture in soil and building envelope the thermal, voltage and resistance based methods are preferable because of their tools that are more portable and costless comparing to infrared and microwave tools.

Figure 32. Measure the moisture content inside the wall the stone and cladding are removed for installing the probe type moisture meter. [**51**]

The comparison of advantages and disadvantages of resistance, thermal, infrared and microwave methods are explained in the table11.

Table 20.Comparison of measurement methods for moisture content

Measurement Technique	Advantages	Disadvantages
Resistance based method	Good sensitivity Inexpensive Easy sensor installation Simple sensor technology Can setup remotely measurement	Destructive Temperature affect the accuracy Low accuracy in low amount of moisture
Thermal based method	Simple sensor technology Inexpensive Easy sensor installation Can setup remotely measurement	Low accuracy Temperature and electrical conductivity changes affect the accuracy
Infrared	Contactless method Accurate Can setup remotely measurement	Can measure just surfaces Expensive Surface aging affect the accuracy
Microwave	Accurate Non-destructive Can setup remotely measurement	Low accuracy in very low and very high amount of moisture Wave can be spread-out

Notes for table: Surface aging affect the accuracy: Age of surface is affecting the result.

Contactless method: measuring does not need to contact with materials, with distance is possible as well.

Destructive: damage the material

Remote measurement can also be set up: leave the sensor after installation and automatically measure.

Wave can be spread-out: scattering may happen during the measurement.

4.4.2.4 Standards validate methods

The ASTM standard describes the application of almost all moisture sensors in mechanical methods, for example

- ASTM G84-89 (2005) application of the Sereda moisture sensor in voltage method.
- ASTM Standard C 1153 -97 (2003) is practice applies techniques that work infrared imaging to determine the location of wet insulation in roofing systems at night.
- ASTM E168-99 (2004), and ISO 6781-1983, Relevant standard IR.

The following are other related moisture standards of ASTM listed D 4643-08, F 1869-10, D 1558-10, C 1699-08, C 1363-11, D 4444-08, C1498-04 and etc. that is illustrated in chapter 2.

4.4.2.5 Find Out the Condensation Take Place In Building Components

Some places like bathroom, laundry room, kitchen, basement; the amount of moisture is more than the other places in the house, so the condensation is more likely to appear in these places. Where the pipes are located in the building depends on the HVAC system and water system map the appearance of the condensation is more predictable than the other places in the house.

To find out condensation places in building component, the numerical calculation can be obtained to be used as an input of the simulation software. Simulation software with more detail information about HVAC and water system will give better result of the places of condensation. Checking the simulation program comparison tables provided in this thesis and choose the right tools for each situation to find out the place of the condensation. These tools provide enable the user to have accurate prediction and measurement of the condensation

4.4.2.6 Following the Moisture Movement in Building Construction

Moisture transport, or movement, occurs in two states: liquid and vapor. That is related to pressure differentials. For example, water in the form of vapor will move as warm moist air from its high-pressure area to a lower-pressure area where the air is cooler and drier.

Liquid water will move as a result of differences in wind pressure. It is the pressure differentials that drive the rate of moisture migration in either state. Because the building materials themselves resist this moisture movement, the rate of movement will depend on two factors:

- The permeability of the materials when affected by vapor.
- The absorption rates of materials in contact with liquid.

Now, to follow the movement of moisture, the mechanical tools can be used to find out the way of the moisture move.

For example to follow up the movement of the moisture for exterior surfaces the Infrared tools give good result by taking images during the long time. By comparing the images with each other the movement of the moisture can be identified. The good thing about Infrared tools is that by taking images, the large area of a building can be examined in each run. The Infrared tools can also identify the interior moisture movement inside the building by again taking the images from inside surfaces. Infrared tools can identify moisture movement that causes by pressure differentials, solar radiation from outside, interstitial condensation and etc.

Chapter 4

CONCLUSION

Nowadays constructing a green building is one of the key issues for architects. Green building construction is a big issue that controlling the moisture content in buildings is one of the most important issues in building construction because of the hazards that moisture can brings to people's health like allergies, breathing disease and skin disease other than the harmful problems that moisture can make to building foundation sustainability and building materials in terms of interior and exterior.

By controlling moisture content in buildings other than building durability, less energy consumption can be obtained by predicating the moisture content in design stage and controlling it after construction is finished.

Because of the above hazards, prediction and controlling the moisture in buildings acts an important role in building construction. This thesis brings a complete survey on moisture prediction methods (mechanical, graphical, simulation).

In these 3 methods, moisture measurement by mechanical methods, moisture prediction by graphical methods that include Glazer and dew point that is working with some mathematical equation and moisture prediction by simulation programs, introduce the methods and compared different techniques and tools in each method. Different problems that may occur in a building such as condensation, water leakage, and moisture movement are also examined and the solution to each problem is suggested.

There is not one best methods or software that will be completely satisfy all users and requirements. The usage of methods and software tool depend on the situation; Design stage, construction stage and operation stage.

Sample scenario of a project from first stage to last stage

1. In design stage, finding the geographic location, geometric and etc. of the building or structure.
2. Find out the climate data (annually, daily, and hourly) of the location.
3. Find out the material of the building or structure.
4. In design stage, graphical methods are useful depend on the situation of the building that find out the condensation in building and building component with less cost.

   The other method that can be used in design stage is simulation software that are useful to predicate and analyse the whole building or some parts of building with all input data. Selection of a good simulation program in design stage by considering all needed features, the process of preventing, detecting and removing moisture content will be easier.
5. The result of the simulation software and mechanical tools are very important for architecture to design and construct a durable building or structure. In this step architecture can design the building with all data that are can be found from simulation tools.
6. In operation stage or existing building can be maintained and evaluated by using mainly mechanical tools to prevent from any harmful hazard that can be done by moisture. Also simulation tools can be used in operation stage by defining new data (existing building) as input of the simulation software.

The Future of Work can be

- Detail analysis of each simulation program
- Analysis of existing mechanical tools in terms of their accuracy, price, maintenance, and etc.
- Detail information about standard codes related to moisture

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