MOISTURE TRANSFER IN POROUS MATERIALS EXPOSED TO
COMBINED HUMIDITY AND TEMPERATURE GRADIENTS

by
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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE
in
MECHANICAL ENGINEERING

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March, 1996
Blacksburg, Virginia
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(ABSTRACT)

Moisture migration is responsible for much damage in modern buildings. Air infiltrations were almost eliminated because of the use of various qualities of materials and insulation. Water is mainly transferred through building materials by diffusion, under three different phases (vapor, liquid and bound). Most of the time, indoor and outdoor conditions are different and strong gradients of humidity and temperature exist within the building walls.

Many models describing moisture diffusion through capillary-porous materials exist, but none of them is universally accepted. The proposed work includes a presentation of these theoretical models which will be implemented and evaluated by a series of experiments. Data is obtained for Oriented Strand Board (OSB).

The existing apparatus, developed by Crimm (1992) and Mosier (1994) consists of a wood-based sample, sealed between two environmental chambers. Each chamber has its own humidity and temperature control system. This apparatus is an alternative to the standard “cup” method to determine moisture permeability of wood samples. The relative humidity is not controlled by salt solutions. Forced air circulation at the surface of the
specimen results in uniform conditions in the chamber and faster results. The experimental apparatus is upgraded for better control. The relative humidity is controlled in a range of 5-75 per cent, within 0.2 per cent of the setpoint, and the temperature can be maintained within 0.05°C, in a range of 15-50°C.

The apparatus operation is validated by comparing a series of isothermal data with published results. Good agreement is found between these data and those reported by two different authors. Several nonisothermal experiments are conducted to implement and evaluate the moisture diffusion theory.
ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. W.C. Thomas, who provided his continuous help and support throughout this project. I would also like to thank my committee members, Dr. J.R. Mahan and Dr. T.E. Diller.

I gratefully acknowledge the American Society of Heating, Refrigerating and Air-conditioning Engineers and the Mechanical Engineering Department for providing financial assistance for this project and for my graduate studies.

I also thank my labmates, John Risi and Joe Edward, not only for the help they gave me, but also for keeping a good atmosphere in the lab.

Most of all, I thank my girlfriend Kristie for the love and support that sustained me through the duration of this project.

Finally, I would like to dedicate this thesis to the memory of my grandmother, “Sarcelle” Chevrier who died in my home-town in August 1995, while I was working here on my project. May she rest in peace.
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>surface area per sorption site (m²)</td>
</tr>
<tr>
<td>C</td>
<td>total concentration of the system (mol/m³)</td>
</tr>
<tr>
<td>Cₚ</td>
<td>heat capacity (J/kg°C)</td>
</tr>
<tr>
<td>Dₜ</td>
<td>bound-water diffusion coefficient</td>
</tr>
<tr>
<td>Dₚ</td>
<td>mass transfer coefficient due to temperature gradient (m²/s°C)</td>
</tr>
<tr>
<td>Dₘ</td>
<td>moisture diffusivity (m²/s).</td>
</tr>
<tr>
<td>Dₙ</td>
<td>coefficient of mass conductivity</td>
</tr>
<tr>
<td>Dₘ'</td>
<td>coefficient of moisture diffusion</td>
</tr>
<tr>
<td>E</td>
<td>activation energy (E=Eₜ+Eₙ)</td>
</tr>
<tr>
<td>Eₜ</td>
<td>frictional component of activation energy</td>
</tr>
<tr>
<td>Eₙ</td>
<td>binding component of activation energy</td>
</tr>
<tr>
<td>EMC</td>
<td>equilibrium moisture content</td>
</tr>
<tr>
<td>f</td>
<td>resistance coefficient</td>
</tr>
<tr>
<td>h</td>
<td>relative humidity (P/Pₚₛₜ ) at temperature T</td>
</tr>
<tr>
<td>Hₐ</td>
<td>energy level of the activated molecules</td>
</tr>
<tr>
<td>Hₙ</td>
<td>potential energy wells corresponding to each sorption site</td>
</tr>
<tr>
<td>Hₜ</td>
<td>energy level of water in vapor phase</td>
</tr>
<tr>
<td>Hₚ</td>
<td>energy level of water in liquid and bound phase</td>
</tr>
<tr>
<td>J</td>
<td>molar flux (mol/m²s)</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant</td>
</tr>
<tr>
<td>Kₘₚ</td>
<td>heat transfer coefficient from moisture migration (W/m)</td>
</tr>
<tr>
<td>Kₘₚₜ</td>
<td>coefficient for diffusion of activated moisture molecules</td>
</tr>
<tr>
<td>Kₜₗ</td>
<td>thermal conductivity (W/m°C)</td>
</tr>
<tr>
<td>Kₙₜ</td>
<td>coefficient of diffusion, based on the chemical potential μ</td>
</tr>
<tr>
<td>L</td>
<td>latent heat (J/kg)</td>
</tr>
</tbody>
</table>
m*  mass flux (kg/m²s)
M  moisture content (kg/kg)
M*  content of activated moisture molecules in the wood based on oven dry weight
M_w  molar weight of water (kg/mol)
P  partial pressure of water (Pa)
P_total  total gas pressure (Pa)
P_o  standard pressure (Pa)
Q*  thermal heat of transfer (atm)
R  gas constant (J/mol.K)
RH  relative humidity (%)
S  the molar entropy (J/mol.K)
T  temperature (°C)
u  mean velocity of molecules (m/s)
V, V_m  molar volume of the gas, assumed ideal (m³/mol)
W_g  green wood mass (kg)
W_o  oven-dried mass (kg)

Greek
α  attenuation factor for vapor diffusivity in wood, dimensionless
α  area ratio of the cell wall cross section to the available cross section
θ  mass potential (°M)
φ  spreading pressure
φ₀  value of φ when h=1
μ_b  chemical potential of bound water (J/kg)
μ_v  chemical potential of water vapor (J/kg)
μ*(T)  standard chemical potential of the substance at temperature T (J/kg)
ρ  density (kg/m³)
ρ_c  density of the cell wall
τ  tortuosity of the cell wall
CHAPTER 1

Introduction

Energy conservation is a major concern in the building industry. It should be considered as the avoidance of unnecessary energy use. After 1970, there was a sharp escalation in petroleum prices, soon followed by increases in the cost of electricity, gas, and coal. It immediately became economically imperative for customers to reduce energy purchase costs as much as they could. The effort to reduce energy use became a concern of governments, and energy codes calling for better performing building were developed. Air leaks at windows and doors have been reduced by better construction, closer tolerances, and better weather-stripping. In most new buildings, infiltration has been almost eliminated. The amount and quality of insulation was increased as well. Thermal resistance was then higher, but it led to surprising damage in the structure of buildings. An increase in indoor humidity is a result of tight building because of reduced air ventilation and infiltration, and high humidity is of great importance for human health and comfort.

The importance of the moisture problem for the building industry, which is the main motivation for this research, is introduced in this chapter. Several important concepts will also be defined. The scope and limitation of this research will then be presented.
1.1. Human comfort, health and air quality

Since water vapor is a natural component of atmospheric air, either natural or forced infiltration introduces moisture in the edifice. Water vapor also comes from human activities, such as cooking, laundering, and occupants’ respiration. According to the ASHRAE Fundamentals (1981), daily water vapor production can exceed 11 kg for a family of four.

Large temperature and humidity gradients between the inside and the outside of buildings and seasonal variations could lead to severe structural damage. However, reducing the level of indoor humidity alone is not a solution because a moderate level of humidity is necessary for the health and comfort of human beings.

Thermal comfort is a highly subjective perception, and can be defined as the absence of discomfort, as in no sensation of heat or cold. Cowan (1988) classified the factors affecting thermal discomfort into four categories: (1) the temperature of the air, (2) the mean radiant temperature of the surrounding, (3) the degree of air movement and (4) the relative humidity.

Many indicators of comfort exist. The most widely used one is the new ASHRAE comfort chart, shown in Fig. 1.1. It results from psychological research to define a temperature and humidity zone of comfort. This chart represents the dry-bulb temperature and relative humidity range of comfort on a psychometric chart, for a sedentary, lightly clothed person, with an air velocity of 0.2 m/s, during one hour. The data show no important
changes with long-term exposure. Comfort occurs, for sedentary people, when regulatory sweat is zero.

![ASHRAE comfort chart](image)

**Figure 1.1** ASHRAE comfort chart, adapted from ASHRAE Fundamentals (1993)

Man's health is strongly dependent upon the indoor and outdoor environment as well. Since humans spend about 95 per cent of the time indoors (ASHRAE Fundamentals, 1989), the control of the atmosphere is important. The indoor concentration of bacteria and viruses is generally higher than the outdoor concentration, and transmission among people is easier indoors. A study by Green (1975) shows a relationship between indoor relative humidity and absenteeism and colds on school children and army recruits. This study suggests that an
increase of the relative humidity from 22 per cent to 35 per cent leads to a drop of 20 per cent

Figure 1.2. Survival of air-borne micro-organisms as affected by relative humidity (from Green, 1975).

in all absenteeism. Dry environments are favorable for the growth of numerous bacteria. Figure 1.2 represents the percentage of survival microorganisms after a long period in a constant environment. It shows that the concentration of bacteria depends strongly upon the relative humidity. Other factors influence the rate of survival, such as the temperature and the type (and size) of the microorganism.
Indoor air quality is affected by relative humidity. At high humidities, microorganisms, like mildew and mold, grow on wall surfaces. Biological contaminants are then more likely to develop. A very dry environment promotes the growth of biological organisms and pathogens as well, as shown in a study conducted by Sterling (1985). Figure 1.3 shows the optimum relative humidity range for health.

The amount of moisture in buildings is not only important for humans, but it is critical for the durability of the construction. The presence of excessive moisture in building materials induces several effects that can lead to structural damage. The different effects are presented in the next section, as well as the consequences on the edifice.

1.2. Water in building materials

Building materials and components are subject to the effects of a number of agents,
some of which may influence their performance and durability and therefore lead to failure. Weather is the main agent of structural damage. The principal components of weather are as follows: solar radiation, rain, solidified water (snow or hail), air and its components (water vapor, oxygen, carbon dioxide, ...), and contaminants of air (dirt, salts, ...). Durability and performance are also affected by biological agencies, among which fungi, mold and insects are the most important (Ramson, 1981). Moisture, in solid, liquid or gaseous form is the most important agent causing deterioration. It is always present in the atmosphere and, when the temperature drops, condensation occurs. Water is slow to evaporate because of its high heat of evaporation. Therefore, materials can remain wet for a long period of time. Metal corrosion, biological growth, etc. occur and these conditions are highly favorable for deterioration.

1.2.1. Moisture content in wood

Water in a living tree is transported from the roots to the leaves, as a result of a pressure gradient. When a tree is cut, water columns are ruptured and water ceases to flow in the tree. The moisture content in the wood (M) at that time is called the “green” moisture content. It varies considerably among kinds of trees, but it also depends upon size, age, climatic conditions, etc.

Moisture content is defined as the quantity of moisture in wood, expressed as a percentage of oven-dry mass (mass of the wood after being dried at 102 ± 3°C):
where \( W_g \) is the green mass and \( W_o \) is the oven dried mass.

The "fiber-saturation point", \( M_f \), is defined as the moisture content at which the cell walls are fully saturated but the cell cavities contain no free liquid water (Fig. 1.4).

\[
\frac{W - W_o}{W_o} \times 100
\]

\( W \) is the green mass and \( W_o \) is the oven dried mass.

![Diagram](image)

**Figure 1.4.** Schematic diagram showing an idealized representation of the moisture distribution in a wood cell cross-section, above, at and below \( M_f \).

The presence or absence of water in a liquid form in the cell cavities have an important effect on numerous properties of wood. The variations of these properties usually show a discontinuity around the fiber saturation point (see Fig. 1.5). This discontinuity is used to determine the fiber-saturation point. Several main properties are discontinuous when passing the fiber saturation point. For example, several mechanical properties such as strength are affected. Electrical resistance also changes with moisture content.
1.2.2. Effect of moisture on materials

Many building materials have a large surface area as a result of the number of interstices, which can be interconnected or not. This internal surface area has an affinity for water molecules. Water molecules are held to the surface by molecular forces of attraction (surface adhesion). A water film forms on the surface. The film thickness depends upon the relative humidity (RH) which is a function of the temperature and the concentration of water vapor. At saturation conditions, all the interstices will be filled with water. Moisture content has a great impact on the moisture flow in capillary-porous bodies. The presence of water in the material induces three different effects that are identified as sources of structural and thermal degradation.

Effect of moisture on dimensions

Dimensional changes occur in many hygroscopic materials, most notably in wood. However, wood undergoes dimensional changes from different causes than other hygroscopic materials. Thermal expansion of wood is small, and usually considered unimportant for ordinary usage. Significant dimensional changes occur with moisture content variations. According to ASHRAE Fundamentals (1981), swelling and shrinkage of white oak is about 1.5 per cent in a radial direction and 3 per cent in a tangential direction to the grain, at an 8 per cent variation in moisture content.
**Effects on the strength of wood**

The strength and mechanical properties of wood usually increase with a decreasing moisture content below the fiber saturation point. Above the saturation point, there are no changes with an increase or decrease of moisture content.

An example of changes in strength properties is given in Fig 1.5. A linear variation is shown between moisture content and a certain strength property. The actual variation around the inflection point (\(M_p\)) is shown in the dashed curve. For most species, \(M_p\) is from 21 per cent to 28 per cent, and is usually around 25 per cent. The inflection point (\(M_p\)) is usually considered to be equal to the fiber-saturation point (\(M_f\)).

![Figure 1.5. Variation of strength with moisture content (from Gurfinkel, 1973)](image)

**Moisture effect on heat flow**

Moisture in buildings may strongly affect heat transmission through them. It can increase the thermal conductivity largely by adding to the path available for heat flow.
It has been shown that in porous material partially and uniformly saturated with water, moisture will migrate to the cold side when submitted to a temperature gradient only (Thomas, 1983). This phenomenon occurs mainly through the process of evaporation, vapor flow and condensation within the material. Heat is transferred as latent heat of the vapor. Heat must be added to evaporate water and must be removed to condense water.

Moisture diffusion into partially saturated hygroscopic and porous material occurs as a kind of series-parallel flow of vapor and liquid. The two types of flow (liquid and vapor) cannot be separated, since they are closely coupled by evaporation and condensation.

Cases of combined heat and moisture transfer are extremely complicated, since neither is independent of the other. Depending upon the conditions, liquid and vapor can migrate in opposite directions. Moreover, gravity can play a role in the migration of the liquid phase.

1.2.3. Structural damage and vapor retarders

Structural degradation is most often the result of excessive water in the material. Physical changes, like wood expansion as a result of repeated cycles of freezing and thawing, and chemical modifications, such as steel rusting and the growth of biological organisms, are induced by the presence of moisture in the building construction.

Five sources of water entry into a building have been identified (Ransom, 1981). Moisture entry in a building can occur from any one or more of these sources:
1. Water is largely used during construction, for fixing the concrete for example. The amount of moisture is fairly high during the first years.

2. Ground water migrates into the materials in contact with the soil, by capillary action. The height to which ground water can rise can be considerable. Ground water usually contains salts in solution which tend to move toward the surfaces of walls, and stain them.

3. Liquid water can come from infiltration through gaps in the structure, during rain or snow. It may also enter the building by indirect penetration, through porous materials by capillary forces.

4. As shown in §1.1, a great amount of moisture is produced by human activities, and these activities could lead to condensation on surfaces. One person, by breathing alone, produces 0.3 l of moisture a day. Domestic activities, like clothes washing and drying, is also a major source of moisture.

5. The presence of moisture in air can lead to condensation. Condensation occurs where the temperature drops below the dew-point.

In moderate climates, heating buildings during the winter causes large indoor humidity variations because of outdoor temperature variations. An example for annual variation of indoor and outdoor humidities is shown in Fig.1.6. These values are monthly averages of outdoor temperature and humidity in Amherst, Massachusetts assuming a constant indoor temperature of 21°C. Water freezes in the pores of the building materials, such as brick or stone, and exerts a force whose magnitude depends upon the quantity of water in the
material. Although these expansive forces can lead to fractures, frost damage is generally not important in building failures. When damage has occurred, it usually affects the appearance more than the stability of the wall. Repeated cycling of heating and freezing can lead to more severe structural damage.

![Graph showing annual variation of outdoor and indoor humidity](image)

Figure 1.6. Annual variation of outdoor and indoor humidity $H$ at Amherst, MA (from Skaar, 1988).

Under certain moisture conditions, wood can be attacked by decay-producing fungi and insects. A series of parasitic microorganisms known as fungi lead to destruction by decay. They derive their food from the wood cell and therefore they affect the strength of the material. At advanced stages of decay, wood becomes either soft and spongy, or stringy or crumbly. Two types of insects are usually considered - those that attack the wood before it has been cut and those that attack afterward. The first group includes ambrosia beetles or timber worms, and the second includes insects such as termites. Termites can cause serious damage and the only practical solution is to impregnate the wood with preservatives.
Vapor retarders are used to control the flow of water through the building envelope. When placed in a proper location, they function to reduce or eliminate condensation. They should be placed as close as possible to the warm side of the wall, at a location where they will be kept above the dew point temperature of the humid area. Water retarders comprise a wide range of materials, such as asphalt coating, polyethylene sheets, kraft paper and some paints. Frequently, the function of a vapor retarder (to stop vapor diffusion) is combined with the function of an air barrier (to stop the transportation of vapor by air movement) in a composite air-vapor barrier.

The effectiveness of a vapor retarder is expressed in "perms". In English units, 1 perm equals 1 grain\(^1\) per square foot per hour per inch of mercury. It is used to compare vapor retarders. The lower the perm value, the better the vapor retarder.

1.3. Scope of this research

The prevention of structural damage in edifices is a major concern in the building industry. Despite the importance of moisture problems, a practical method to determine moisture transfer is not available.

The scope of this thesis consists of implementing the diffusion theory of moisture in capillary-porous bodies. First, the physics of moisture transfer will be introduced. The main isothermal and nonisothermal diffusion models based on forms of Fick's first law will then be considered.

\(^{1}\) A grain is a mass unit where 1 lb\(_m\) = 7000 grain.
be presented. Some nonfickian models exist, but they are beyond the scope of this research.

A new approach to modeling moisture transfer in materials is proposed and investigated. The new model accounts for separate processes of vapor diffusion through pore spaces, bound liquid transfer along the matrix of the material, and the effect of temperature gradients. This model is based on Fick’s law, where a common driving force, the gradient of the chemical potential of water, is used for both transfer mechanisms.

The proposed work includes upgrading the existing experimental apparatus, verifying its operation, developing experimental procedures for characterizing the test material, and conducting measurements to implement and evaluate moisture diffusion theories.

Limitations

Since the purpose of this research is to identify the driving force for the moisture transfer in capillary-porous bodies, the system studied has to be simple and limited.

While some structural materials are essentially isotropic, i.e., with nearly equal properties in all directions, wood has three principal grain directions (longitudinal, radial and tangential). Internal pores have a preferred orientation that can vary from one sample to another, or within the same sample.

 Builders usually use wood-based sheet materials for many reasons (strength, cost, etc). Two different types exists: fiberboard (made from wood reduced to a fibrous mass which is reconstituted using adhesive) and particle board (composed of small particles of wood coated with a bounding agent). In normal particle board, particle direction,
therefore fiber orientation, is random; but in oriented strand board (OSB), particles are laid with their longitudinal axes in a desired plane. To avoid these complications, moisture transfer is usually considered as one dimensional, across the OSB specimen thickness.

Because of the constant changes in temperature and humidity in building materials (variation between night and day, and from month to month), and the slow evaporation rate of water, steady-state transfer of temperature and humidity are hardly ever reached. However, because of the complexity of nonsteady analysis, this work is limited to steady-state mass transfer. Therefore, the temperature and the humidity are held constant on each side of the specimen for the duration of all experiments.
CHAPTER 2

Moisture Transfer Theories

As noted in the first chapter, the prevention of structural damage in buildings is a major concern in the building industry. Despite the importance of moisture problems in the building industry, a practical method to determine moisture transfer is still not available. Many moisture control design guidelines have been developed, like air barriers or vapor retarders, based on past experience.

Since water vapor is always present in the air, it is present in most building material as a result of absorption, adsorption, or both. It can be in a solid, a liquid, or a gaseous phase. Structural damage results from excess moisture or changes in the moisture content of building material. Condensation causes the most severe problems. It occurs when the temperature of the mixture of air and moisture is below the dew-point, usually because of a temperature drop. Most damage occurs in cold climates during the winter or the spring.

According to TenWolde (1989), the complexity of moisture movement is the greatest obstacle in modeling the moisture transfer. Many theoretical models have been developed, but none of them is universally accepted.
The object of this chapter is to present the different models found in the literature for isothermal and nonisothermal moisture transfer in capillary-porous bodies. Physical arguments on moisture storage and transfer mechanisms will be introduced first.

2.1. Moisture migration: difficulties of transport modeling

Many building materials, like wood or concrete, are porous and hygroscopic. Water is stored in the material and can be transported either through the interstices or by diffusion. Mechanisms of transfer will be presented in § 2.1.2. First, some general notions about water in building materials will be introduced. Moisture sorption in capillary-porous material is of fundamental importance for moisture transfer. Water sorbed in the material affects its properties, such as porosity, and therefore modifies the moisture transfer.

2.1.1. Moisture content in wood

As shown in Chapter 1, the moisture content of wood (M) is defined as the quantity of moisture in wood, expressed as a percentage of oven-dry mass (mass of the wood after being dried at 102 ± 3°C):

\[
M = \frac{W - W_o}{W_o} \times 100 \quad \text{(percent)}
\]  

(2.1)
where \( W_g \) is the "green wood" mass and \( W_o \) is the oven-dried mass.

The moisture content in a living tree is generally 30 per cent or greater. Under these conditions, the cell wall is fully saturated and the cell cavities contain some liquid water. When cut green wood is exposed to atmospheric conditions, the moisture content decreases until it reaches equilibrium with the ambient atmosphere (Fig. 2.1). This moisture content is defined as the equilibrium moisture content, or EMC. The equilibrium moisture content of a body depends on the temperature, relative humidity of the surrounding air, the method

![Diagram](Figure 2.1. Schematic diagram illustrating the three kinds of moisture in green wood and the two kinds in air-dry wood (from Skaar, 1988))

of reaching the equilibrium (absorption or desorption), and several other factors like mechanical stress, history, etc.
Effect of relative humidity

The relative humidity (RH) is the most important factor affecting the moisture content \( M \) of wood. The relation between \( M \) and RH is called the sorption isotherm. Skaar (1988) describes three types of sorption isotherms (Fig. 2.2).

Type 1 is the sorption of vapor on a substrate in which only one layer of vapor is found on the substrate. Type 3 corresponds to a multilayer sorption. Several layers of vapor are formed on the substrate. The type 2 isotherm is typical of the moisture sorption isotherms of wood and many hygroscopic materials. It appears as a combination of type 1 and 3.

Figure 2.2. Shapes of the three kinds of sorption isotherms (from Skaar, 1988).
Effect of history (sorption hysteresis)

Figure 2.3, shows the isotherm sorption hysteresis for general food products. The equilibrium moisture content is usually higher during desorption than adsorption. A sorption isotherm can be divided into three regions. In region A, the curve is concave to the relative humidity axis, and represents the adsorption of the first layer of water vapor onto the surface of the material. The binding energy is usually high, and depends upon many factors, like the surface and the structure of the adsorbing material and the physical properties of water. In region B, water is more loosely bound to the surface; it corresponds to the second layer of adsorbed water molecules. The energy involved is predominantly that of condensation. Region C corresponds to a deposition of successive layers and capillary condensation. Water is present in large capillarities and relatively free to move.

Figure 2.3. General sorption isotherm for food products (from Fortes, 1980).
Sorption hysteresis exists in every capillary-porous material, such as in wood. This effect decreases with increasing temperature, and disappears at high temperatures (between 75°C and 100°C).

**Effect of temperature**

The sorption or desorption isotherms vary depending upon the temperature, as shown in Fig 2.4. At a given relative humidity, the moisture content decreases when the temperature increases. This trend is valid for temperatures above 0°C and below 100°C. Above 100°C, the same behavior is expected, although it is hard to measure. Below 0°C, the moisture content of wood is expected to decrease when the temperature increases. The decomposition of the wood structure at low temperatures is given as a possible explanation by Skaar (1988).

![Figure 2.4. Desorption isotherms for Sitka spruce at several temperatures (from Stamm, 1964).](image)
2.1.2. Mechanisms of moisture transfer

The objective of this section is to present the current understanding of moisture migration in capillary-porous bodies. According to Gavin (1985), the complicated nature of moisture migration is the greatest obstacle in modeling moisture transfer. Experimental studies account for the bulk of what we know of the problem. Theoretical models usually ignore many potentially important migration effects.

![Mechanisms of moisture transfer](image)

A general description of the problem is given in Fig. 2.5. Moisture migration in building materials occurs in the presence of a non-condensing gas (air) and one or more solid materials (wood, concrete, metal, for example), some of which may be porous. Depending
upon the conditions, moisture can exist in one or more of its three phases, solid (ice), liquid and gas (water vapor). In the presence of a hygroscopic material, a fourth phase may exist, consisting of an adsorbed film of water molecules on the surface of the solid. There is an important distinction between this adsorbed water film (or bound water) and the absorbed water vapor. According to Gavin (1985), large quantities of water can be stored in the adsorbed film phase; for example, wood can adsorb moisture up to 30 per cent on a dry-weight basis.

As shown in Fig. 2.5, a transition between phases can occur. Moisture can be stored and transported in each phase by one or more physical mechanisms, with the exception of the solid phase, which is virtually immobile. Whereas the transport and storage mechanisms of the solid, liquid and gas phase of water are relatively well understood, the transport of moisture associated with the adsorbed phases (referred to as "transorption") is not well known.

All of the mechanisms described in Fig 2.5 are of potential importance to moisture migration in building walls. The importance of each separate mechanism will vary depending on the material used, the exposure conditions, etc. For example, in warm climates, the solid phase is not present, so there is no need to consider the solid phase transport mechanism. But usually several of these transport mechanisms are present simultaneously, and different phases can be involved at the same time.
In practical building applications, three phases of water are considered (liquid, vapor and bound). Water is mainly transported by diffusion (molecular mass transfer) and convection. Some investigations have shown that diffusion is the dominant mechanism for well-constructed walls (Verschoor 1985 and Burch 1989), because these materials do not allow air to move through the walls.

Finally, the moisture migration in building walls is further complicated because: (1) it is a multidimensional and time dependent problem; (2) it is strongly coupled with the energy equation, as pointed out in Chapter 1; and (3) it is subject to boundary-conditions which are difficult to specify and which depend on the moisture transport rate.

Several models have been proposed for both isothermal and nonisothermal diffusion, but none of them is universally accepted. No satisfactory model handling both humidity and temperature gradient have been found yet. The next two sections will present the most used models found in the literature for isothermal and nonisothermal diffusion of water through capillary-porous bodies.

2.2. Isothermal diffusion

When a system has two or more components with non-uniform concentration, mass is naturally transferred in order to make the concentration within the system uniform. This transport of constituents, the mass transfer, can take place by two different mechanisms.
Mass can be transferred by the random movement of the molecules in a stagnant fluid (molecular or diffusive mass transfer) or by the motion of the surrounding fluid (convective mass transfer). These two modes are similar to diffusive and convective heat transfer.

As pointed out before, the scope of this study concerns only the diffusive mass transfer. Before developing the different models for mass diffusion through hygroscopic materials, the fundamentals of mass transfer will be recalled. This section is largely inspired by Welty, Wicks and Wilson (1969). Only one-dimensional binary stagnant systems will be considered.

### 2.2.1. Fick’s law

Molecular diffusion is defined as the macroscopic transport of mass, independent of convection, as a result of the natural movement of the constituents of a thermodynamic system. At temperatures above absolute zero, every molecule has a random motion. A given molecule will collide with other molecules and will move in a random motion. Although it is impossible to predict the path of each individual molecule, it is possible to state that the net flow of the molecular species occurs in the direction of lower concentration.

The governing relations for the mass transfer are referred as Fick’s empirical laws. Fick’s first law states the relation between the flux of the diffusing substance and the concentration gradient responsible for the mass transfer. Consider a binary mixture of
components A and B (either solids, liquids or gases). The molar flux of the component A, in direction x, in an isothermal and isobaric system is expressed as

\[ J_A = -D_A \frac{dC_A}{dx} \quad (2.2) \]

where \( J_A \) is the molar flux of A in the x direction (mol/m²s), \( D_A \) is the diffusion coefficient for component A through component B and \( dC_A/dx \) is the concentration gradient of component A.

A more general formulation of Fick’s first law was proposed,

\[ J_A = C \frac{d}{dx} \left( \frac{C_A}{C} \right) \quad (2.3) \]

where C is the total concentration of the system. Equation 2.3 is reportedly not restricted to isothermal and isobaric systems. In an isothermal and isobaric system, the total concentration is constant, and equation 2.3 can be simplified as equation 2.2.

An equivalent expression of equation 2.2 for the mass flux in the x direction is

\[ m_A' = -D_A \frac{d\rho_A}{dx} \quad (2.4) \]

where \( m_A' \) is the mass flux of A in the z direction, and \( \rho_A \) the mass concentration of A.
The diffusion coefficient is a specific property of a specific system. It depends upon the temperature, the pressure and possibly the composition of the system. The diffusion coefficient is usually given in m²/s or in ft²/h.

Fick's first law was found experimentally, and is restricted to isothermal, isobaric and monophasic systems. As shown in §2.1.2, transport of moisture through capillary-porous materials involves several phases, and is usually nonisothermal. Many early investigators found that Fick's law cannot be used for this kind of transport, and proposed various transport models. Before discussing each specific model, an explanation of the diffusion mechanism in wood will be presented. It is based on fundamental work by Skaar (1988).

2.2.2. General mechanism of bound water diffusion

As shown in §2.1.2, moisture in wood may appear in three different phases, capillary water and vapor in the cell cavities, and bound water in the cell walls. Liquid water moves because of capillary forces and related thermodynamic potential gradients. Vapor pressure and total pressure gradients are responsible for the vapor flow, which may be important in the total moisture movement. However, at low temperatures, such as at room temperature, bound water movement is the most important mechanism.

Skaar (1988) proposed a model for the mechanism of bound water diffusion. Bound water is believed to be sorbed at or near the sorption sites in the cell wall which have a strong
attraction for water molecules. Water polar molecules are attracted by polar hydroxyl groups in the wood by hydrogen bonding. The author considered that the water molecules are attached to sorption sites, and that a particular sorption site may contain several water molecules in its vicinity, depending on the moisture content of the wood. Skaar considered for illustration that the number of molecules of water per sorption site, on the average, is one for every 7 per cent moisture content. Figure 2.6 represents a hypothetical diagram of the moisture distribution in wood, for a non-uniform and a uniform moisture distribution. In both cases the average moisture content is 14 per cent and the fiber saturation point is 28 per cent. The potential energy wells corresponding to each sorption site (H_s) are shown, as well as the energy level of water in vapor (H_v), liquid and bound phase (H_w) at different moisture contents (dashed curve).

From Fig 2.6, it is evident that a water molecule sorbed on a site (at energy H_s) must attain the energy ΔH_v = H_s - H_v in order to evaporate from the wood. Similarly, the same
molecule must attain the energy \( \Delta H_b = H_w - H_b \) to escape into the liquid form. One can note from Fig 2.6 that \( \Delta H_b \) is smaller than \( \Delta H_v \), which explains why the bound phase transfer is more important than the vapor phase transfer.

According to the diagram, a water molecule needs to overcome the energy "barrier" in order to jump from, for example, the 14 per cent sorption site to the 7 per cent. The activation energy (\( E_a \)) represents the height of the barrier, and is equal to \( H_a - H_b \), where \( H_a \) is the enthalpy level of the activated molecules.

Figure 2.6 gives some insight into the reason why bound-water movement takes place in wood, and the direction in which it moves. Water molecules tend to migrate toward dryer wood, because dryer wood contains more low energy sites than moist wood. The rate of movement of bound-water is determined by the height of the energy barrier (\( E_b \)) because the probability of a given water molecule having sufficient kinetic energy to overcome the barrier is inversely related to the height of the barrier. The moisture flux is therefore higher if the energy barrier is lower (i.e. higher moisture content), as shown in Fig 2.7. It shows

---

![Figure 2.7: Bound water diffusion coefficient \( D_b \) in relation to the mean moisture content for the cell wall of Sitka spruce as measured by Stamm at 26.5°C (from Skaar, 1988).](image-url)
a large change in the diffusivity coefficient $D_b$, and therefore the flow rate increases with increasing moisture content.

The relationship between $E_a$ and $D_b$, assuming a concentration gradient as in Fick’s law, is given by the Arrhenius equation,

$$D_b = D_0 \exp \left( \frac{-E_a}{RT} \right)$$  \hspace{1cm} (2.5)

where $D_0$ depends on the concentration and distribution of sorption sites. Equation 2.5 can be used to express the activation energy $E_a$ if the variation of $D_b$ as a function of wood temperature at constant moisture content is known:

$$E_a = RT^2 \frac{d(\ln D_b)}{dT}$$ \hspace{1cm} (2.6)

Skaar presents an exhaustive summary of different workers’ results. Most expressions of $E_a$ are based on the measurement of $D_b$ as a function of $T$, using Eq 2.6, at constant moisture content. Calculation of the activation energy gives values in the order of 8.5 kcal/mol of water. The calculation of $E_a$ as a function of moisture content requires measurements of $D_b$ at each of several moisture contents, as a function of temperature. Such data are not yet available.

Siau (1984) used an approximate equation to calculate the dependency of the activation energy $E_a$ on the moisture content $M$, expressed as

$$E_a = 9200 - 70M \quad (kcal)$$ \hspace{1cm} (2.7)
Equation 2.7 gives reasonable values over the moisture range from 4 per cent to 25 per cent, at a temperature $T$ of 300 K.

In conclusion, the model presented by Skaar is attractive, because it clearly represents the physics of the bound water diffusion mechanism. On the other hand, this model is not easy to use in defining a mathematical model for diffusion for two reasons. First, the activation energy is not a real thermodynamic property, and therefore no exact equation to calculate the dependency of $E_b$ on two thermodynamic properties ($T$ and $P$ for example) exists. Second, the calculation of $E_b$ requires knowledge of $D_b$, the diffusion coefficient assuming a Fick's law based on a concentration gradient, an idea which will be shown to be invalid later.

As pointed out before, a simple diffusion model based on Fick’s first law cannot be used to evaluate moisture diffusion through wood. Other models, simpler than Skaar’s, have been proposed to calculate the moisture flux for isothermal applications. The object of the next section is to present the most commonly used models.

### 2.2.3. Isothermal diffusion models

Most experimental studies on moisture movement have been performed under isothermal conditions, because of the industrial importance of drying, which is often isothermal. Strictly speaking, the transportation of molecules induces some transfer of energy, because of the coupled mass and energy equation. This effect was neglected in most
cases of isothermal moisture diffusion, but has to be considered for nonisothermal moisture transportation.

The controversy in using Fick's law for the analysis of moisture transfer through wood and other similar materials is the assumption that the potential for causing the movement is the concentration gradient dC/dx. Babbitt (1950) first suggested that another potential is involved.

A number of moisture potentials were then proposed by many authors, as shown in Table 2.1. In addition to moisture content, the most used driving forces for Fick's law are the gradients of the partial vapor pressure in equilibrium with the wood, the chemical potential and the spreading pressure. Skaar (1988) has shown that, under isothermal conditions, each transport coefficient $K_i$ can be related to the Fick's law coefficient $D_i$ (Table 2.1.), if the rate of change of the assumed potential with respect to $C$ is known. Calculations using either potential give the same results. Some of the more widely used models will be briefly described, based on the work by Skaar (1988).
Table 2.1: Tabulation of some moisture transport coefficients used for wood, assumed potentials, and relationship to diffusion coefficient $D_0$ (from Skaar, 1988).

<table>
<thead>
<tr>
<th>Assumed potential</th>
<th>Symbol (units)</th>
<th>Transp. coeff. (units)</th>
<th>Relationship to coefficient $D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture conc.</td>
<td>$c$ (g/cm$^3$)</td>
<td>$D = -J/(\partial c/\partial x)$</td>
<td>$D = D$</td>
</tr>
<tr>
<td>Fractional M. C.</td>
<td>$m$ (g/s)</td>
<td>$K_m = -J/(\partial m/\partial x)$</td>
<td>$K_m = D(\partial c/\partial m)$</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>$P$ (erg/cm$^2$)</td>
<td>$K_p = -J/(\partial p/\partial x)$</td>
<td>$K_p = D(\partial c/\partial p)$</td>
</tr>
<tr>
<td>Water activity</td>
<td>$h$ (ratio)</td>
<td>$K_h = -J/(\partial h/\partial x)$</td>
<td>$K_h = D(\partial c/\partial h)$</td>
</tr>
<tr>
<td>Chemical potential</td>
<td>$\mu$ (erg/mol)</td>
<td>$K_\mu = -J/(\partial \mu/\partial x)$</td>
<td>$K_\mu = D(\partial c/\partial \mu)$</td>
</tr>
<tr>
<td>Osmotic pressure</td>
<td>$\pi$ (erg/cm$^2$)</td>
<td>$K_\pi = -J/(\partial \pi/\partial x)$</td>
<td>$K_\pi = D(\partial c/\partial \pi)$</td>
</tr>
<tr>
<td>Spreading pressure</td>
<td>$\phi$ (erg/cm$^2$)</td>
<td>$K_\phi = -J/(\partial \phi/\partial x)$</td>
<td>$K_\phi = D(\partial c/\partial \phi)$</td>
</tr>
</tbody>
</table>

2.2.3.1. Moisture content gradient

The early models for drying and sorption experiments used the gradient of the bound water concentration. Only the bound water diffusion was described, because it was assumed to be the most important transfer. Skaar (1954), Stamm (1959, 1960), Comstock (1963), among others, derived and used these models.

The gradient in the concentration of bound water is expressed either as mass per unit volume or as mass per unit mass of dry wood (moisture content), as shown in table 2.1. The use of $K_m$ and the moisture gradient $dM/dx$ to describe the moisture movement is the same as using Fick's law in its original form, because $K_m$ is related to $D$ by a constant. The slope
dC/dM decreases with increasing moisture content as a result of the swelling of wood (Skaar, 1988).

However, as pointed out by Stanish (1986), the diffusion coefficients derived using this approach were strong functions of temperature, moisture content and wood properties. Bramhall (1976) recognized this disadvantage, and proposed to use the gradient in vapor pressure instead of the concentration gradient as the driving force.

2.2.3.2. Vapor pressure gradient

Bramhall (1976) and Wenger (1977) pointed out some difficulties in using Fick’s law to model diffusion of moisture through wood, and proposed the gradient in vapor pressure as the correct driving force. Many papers were then published to exchange ideas and thoughts: Rosen (1976), Bramhall (1977), Babbitt (1977), Bramhall (1979), among others. The moisture flux of bound water, using the gradient of vapor pressure as the driving force is expressed as

\[ J = - K_p \frac{dP}{dx} \]  \hspace{1cm} (2.8)

where J is the moisture flux (kg/m²s) and P is the partial water vapor pressure.

Numbers of papers were published using this gradient and it is now the most used driving force. It is widely used to describe the transportation of vapor through non-porous
materials such as polymer films used for vapor barriers. The coefficient $K_p$ is often called the “permeability constant”.

2.2.3.3. Chemical potential gradient

The chemical potential (or Gibbs free energy) is used to determine whether equilibrium has been reached in a thermodynamic system. Chemical equilibrium can be defined as the condition when all chemical reactions have reached equilibrium so that the concentration of all chemical components is unchanging.

According to McGlashan (1979), the chemical potential $\mu$ for a real gas is given by the equation

$$
\mu(T,p) = \mu^o(T) + R \ T \ln \left( \frac{P}{P^o} \right) + \int_{\infty}^{P} \left( \frac{V_m \cdot RT}{P} \right) dp
$$

where $\mu^o(T)$ is the standard chemical potential of the substance at temperature $T$, $R$ is the gas constant, $P$ is the partial pressure of the ideal gas, $P^o$ is the standard pressure and $V_m$ is the molar volume of the substance.

The chemical potential of the water vapor, assuming that water vapor is an ideal gas, is usually defined using

$$
\mu(T,p) = \mu^w(T) + R \ T \ln(h)
$$
since the relative humidity $h$ is defined as $h = p/p_{\text{sat}} = \text{RH}/100$. The symbol $\mu^\text{sat}$ denotes the chemical potential of water vapor at the saturation pressure at temperature $T$.

Kawai et al. (1978, 1980) used the chemical potential to express the bound water diffusion for isothermal drying. At a constant temperature, the driving force is expressed as

$$\frac{d\mu}{dx} = RT \frac{d\ln P}{dx}$$

(2.11)

The calculated diffusion coefficient was exponentially related to the moisture content, although data showed considerable scatter at any given moisture content. According to Stanish (1986), the most probable explanation for the data scatter is that the author did not take the vapor diffusion into account. Siau (1980) and Skaar and Siau (1981) used a thermodynamical approach to define a transport law using the chemical potential. According to their work, the moisture flux is driven by the chemical potential gradient under isothermal conditions. They further used their model for nonisothermal moisture transfer, as shown in § 2.3.

2.2.3.4. Spreading pressure gradient

Babbitt (1950) questioned the applicability of Fick's law to the drying of wood. He suggested using the pressure gradient as the driving force, basing his argument on fluid dynamics. The steady-state flow of moisture due to a pressure gradient (spreading pressure) is opposed by an internal resistance force.
Skaar and Babiak (1982) and Nelson (1986) adapted Babbitt's transport model using the Dent (1977) modification to the BET sorption theory. An extensive description of both Dent and BET sorption theory is given by Skaar (1988). In both sorption theories, water is assumed to be sorbed in two forms. The primary molecules are sorbed directly on primary sorption sites, with high binding energy, such as the hydroxyl group. Secondary molecules are sorbed on secondary sorption sites, with lower binding energy and may be considered as supersorbed on primary sites or other secondary sites, as shown in Fig. 2.8. The two theories differ in that the BET sorption model assumes that the thermodynamic properties of the secondary molecules are identical with those of liquid water, whereas the Dent model assumes they are different. Both models assume that the properties of the secondary molecules are identical in all various layers (second, third,...). The Dent model is used to predict sorption isotherms, which are the relationships between the moisture content $M$ and the relative humidity $RH$, using some measured properties. The key relationship is

$$M = RH / [A + B \times h - C \times h^2]$$
where \( h = \frac{RH}{100} \), \( A = \frac{1}{[m_0b_1]} \), \( B = \frac{b_1 - b_2}{[m_0b_1]} \), \( C = \frac{b_1(b_1 - b_2)^2}{[m_0b_1]} \). In practical applications, \( A \), \( B \) and \( C \) are calculated using linear regression from measured sorption isotherms.

The spreading pressure \( \varphi \), as defined by Babbitt (1950),

\[
\varphi = \frac{\partial G}{\partial a} \tag{2.12}
\]

is equal to the change in free energy \( G \) per unit area \( a \), defined as the area per water molecule when there is one molecule on each site. Siau and Babiak (1982) have expressed the spreading pressure in terms of film surface area as

\[
\varphi = \frac{kT}{a} \ln \left( \frac{1 + b_0h - bh}{1 - bh} \right) \tag{2.13}
\]

where \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, \( a \) is the surface area per sorption site, \( h \) is the relative humidity \((p/p_{\text{sat}})\) at temperature \( T \) and, \( b \) and \( b_0 \) are constants from Dent’s sorption isotherm.

Nelson (1986) approximates Eq 2.13 by an empirical equation of the following form, at constant temperature

\[
\frac{\varphi}{\varphi_0} = K h^n \tag{2.14}
\]

where \( \varphi_0 \) is the value of \( \varphi \) when \( h=1 \) in Eq 2.13, \( K \) is a constant ranging from 0.94 to 0.96 and \( n \) varies between 0.65 and 0.85. The quantities \( K \) and \( n \) depend upon the sorption isotherm and weakly upon the temperature.
The flux of bound water can be expressed using the basic law from Babbitt (1950). It comes from a balance between driving force and resistance force:

\[-u = \frac{1}{f} \frac{d\varphi}{dx}\]  \hspace{1cm} (2.15)

where \(u\) is the mean velocity of molecules diffusing in the direction of decreasing gradient of \(\varphi\) and \(f\) is the resistance coefficient. The flux of water, \(-J\), corresponds to the flux of dissociated molecules as

\[-J = \frac{\rho_c M}{f} \exp \left( -\frac{E_b}{RT} \right) \frac{d\varphi}{dx}\]  \hspace{1cm} (2.16)

where \(\rho_c\) is the density of the cell wall at the current value of moisture content \(M\), and \(E_b\) is the binding component of the activation energy \(H_s - H_b\) (also called the energy of dissociation) as defined in §2.2.2. Nelson (1986b) gives an expression for the mobility coefficient \(1/f\).

\[\frac{1}{f} = \frac{D_0}{M} \alpha \exp \left( -\frac{E_r}{RT} \right) \frac{d\varphi}{dM}\]  \hspace{1cm} (2.17)

In Eq. 2.17, \(D_0\) is a constant, \(\alpha/\tau\) is a geometric factor (\(\tau\) is the tortuosity of the cell wall and \(\alpha\) is an area ratio of the cell wall cross-section to the available cross-section), and \(E_r\) is the frictional component of the activation energy. Combining Eqs 2.16 and 2.17, the equation for the mass flow of bound water per unit area and per unit time, in terms of moisture content \(M\), is
The corresponding activation energy $E$ can be expressed as

$$E = E_s \cdot E_r = Q_w \cdot \frac{RT}{n} \cdot E_r \quad (2.19)$$

Equation 2.18 is similar to a Fick’s law, except for the geometric factor and the exponential term. Therefore, the diffusion coefficient $D$ can be written as

$$D = D_0 \frac{\alpha}{\tau} \exp \left( \frac{Q_w \cdot \frac{RT}{n} \cdot E_r}{RT} \right) \quad (2.20)$$

Nelson then compared the model prediction for the diffusion coefficient to experimental data from Stamm (1959), for metal-filled Sitka spruce, at 25.5 °C. In Eq. 2.20, $D_0 = 0.197$ cm$^2$/s, $E_r = 5,300$ cal/mol, and $n = 0.786$. The variation of $\alpha/\tau$ and $Q_w$ with temperature are neglected, so they are both expressed as a function of $M$ only:

$$Q_w = 4,826 \exp (-13.78 M)$$

$$\frac{\tau}{\alpha} = 2 \cdot \frac{0.9 M}{0.685 + 0.9 M} \quad (2.21)$$
As shown in Fig 2.9, there is good agreement between the experimental values from Stamm (1959) and the values for the diffusion coefficient $D$. The quantity $\tilde{D}$ represents the integral diffusion coefficient defined as

$$\tilde{D} = \frac{1}{M_f - M_i} \int_{M_i}^{M_f} \frac{0.685 \cdot 0.9 M}{2.653 \cdot 0.9 M} \, D \, dM$$

In Eq. 2.22, $M_i$ and $M_f$ are the initial and final adsorption moisture contents, estimated from the sorption isotherm of Sitka spruce of Stamm and Loughborough (1935). The ratio factor converts the local values of $D$ from a wood substance to a wood specimen basis.

This model developed by Nelson (1986a, 1986b) is similar to Fick’s law, except that it includes two terms, one for the activation energy and one geometric factor. This model can be derived using Babbitt’s work on diffusion in solids (1950). The Dent (1977) spreading pressure relationship is used to calculate the energy required for water molecules to become activated and move from the sorption sites. However, this model requires experimental data. For example, the variation of $Q_a$ and $\alpha/\tau$ with the moisture content and
the temperature are required for the calculation of the diffusion coefficient. Such data are not available; therefore, it is impossible to test this model for other wood species, at different temperatures.

2.3. Nonisothermal moisture diffusion

Most of the early studies of moisture movement in wood were conducted under isothermal conditions. Understanding isothermal diffusion of moisture is of great importance to the drying industries. Analyses were carried out without taking account of the thermal effect on moisture diffusion, for experimental reasons. However, for energy conservation studies, and even some drying applications, such as microwave drying techniques, the movement of moisture as a result of a temperature gradients may be significant.

The objective of this section is to present principal diffusion models for nonisothermal moisture movement found in the literature. The importance of the thermal effect (Soret effect) in moisture diffusion in wood will be introduced first. The next section will emphasize the necessity for a moisture diffusion model by summarizing the fundamental work of Luikov (1966) on the coupled heat and mass transfer equations. The last section will focus on a presentation of the most important nonisothermal diffusion models found in the literature.
2.3.1. The Soret effect

The preceding discussion has been confined to isothermal moisture diffusion, in which temperature effects have been neglected. As shown in §2.1.2, even in isothermal conditions there is some coupling of heat and mass transport, through the evaporation-condensation process.

In most practical applications, temperature gradients are present and the coupled effect of moisture and temperature gradients cannot be neglected. One such coupling phenomenon is known as the Soret effect. This effect is the process when moisture moves as a result of a temperature gradient. When wood is only subjected to a temperature gradient, the moisture distribution will no longer be uniform but will approach a nonuniform moisture distribution such as that shown in Fig. 2.10.

![Figure 2.10. Moisture and temperature distribution curves in a wood sample subjected to a temperature gradient (from Skaar, 1988).](image)

This coupling of moisture and temperature distributions has been confirmed by a number of researchers, including Voigt (1940), Choong (1963), Bomberg (1978), and Siau (1983). Choong (1963) used the following experimental procedure. Eight test samples of
Western fir (*Abies* sp.) measuring 4 × 4 × 4 cm were prepared and divided to give two sets of four samples for each of the two structural directions of moisture movement (radial and longitudinal). Each of these four sample sets was conditioned to a moisture content of approximately 4, 8, 12 and 16 per cent. Holes were drilled on both sides, perpendicular to the moisture movement for monitoring the moisture content and the temperature distribution, as shown in Fig. 2.11. The external surfaces were then coated with several layers of vapor barrier. They were then subjected to a constant temperature of about 60°C on one side and

![Diagram showing the location of electrical resistance and thermocouple wires inside a test specimen (from Choong 1963).](image)

The test samples remained in the assembly for several weeks until they attained a steady-state condition with respect to the temperature and moisture distribution. The moisture distribution was obtained by slicing each sample into 16 equal-sized wafer samples and weighing them before and after being dried in a oven at 105°C. Results are given in Fig 2.12, and are similar to the expected profile given in Fig 2.10.
Figure 2.12. Moisture content and temperature distribution in samples subjected to imposed temperature gradients for different initial average moisture contents (from Choong, 1963).

2.3.2. Heat and mass transfer equations

Traditionally, most models use Fick's law to describe mass transfer. The key assumption is that the driving force for moisture migration in a capillary-porous material is only due to the moisture gradient. Luikov (1966) derived the differential equations for heat and mass transfer in capillary-porous bodies to take into account the temperature effect on moisture transfer.
The coupled heat and mass transfer equations in the generalized form are expressed by Zhou et al (1994) as
\[
\rho C_p \frac{\partial T}{\partial t} = \nabla.(K_T \nabla T) - \nabla.(K_M \nabla M) + \rho L \frac{\partial M}{\partial t} \\
\frac{\partial M}{\partial t} = \nabla.(D_T \nabla T) - \nabla.(D_M \nabla M)
\]
(2.23)

where, T is the temperature (°C)

M is the moisture content (kg/kg)

\( \rho \) is the density (kg/m³)

Cp is the heat capacity (J/kg°C)

L is the latent heat (J/kg)

K_T is the thermal conductivity (W/m°C)

K_M is the heat transfer coefficient resulting from the moisture migration (W/m)

D_T is the mass transfer coefficient resulting from the temperature gradient (m²/s°C)

D_M is the moisture diffusivity (m²/s).

These two equations are time dependent and are mainly used for drying applications, which is not the purpose of this research. Numerous papers has been published on how to solve these equations for particular applications.

The controversy in using Fick’s law is that the gradient of moisture content is assumed to cause the movement of moisture in a capillary-porous body. By analogy with heat potential (temperature), Luikov (1966) introduced a thermodynamic parameter, the mass transfer potential \( \Theta \). According to the author, the mass transfer potential must be some function of the moisture content and the temperature. The mass flux is therefore given by
\[
J = -D_\Theta \nabla \Theta
\]
(2.24)
where $D_\theta$ is the constant of proportionality called the coefficient of mass conductivity, similar to the coefficient of thermal conductivity in Fourier's law. Whereas the heat transfer potential (temperature) is measured directly, an experimental scale of mass potential $\theta$ is necessary to adjust some differences in the standard specimens. The mass transfer potential is expressed in mass transfer degrees ($^\circ$M), where $\theta$ equal to 100$^\circ$M is obtained at the point of maximum hygroscopy (i.e. the hygroscopic region is for $\theta$<100$^\circ$M). For more details on how to measure the mass potential, one can refer to Luikov (1966).

Figure 2.13 shows some experimental values of $\theta$ as a function of the moisture content, for different temperatures.

As shown in Fig 2.13, the curves $M=f(\theta)$ have different shapes, depending on the kind of moisture bond. The slope $(\partial M/\partial \theta)_T$ increases continuously with the increase of mass potential $\theta$. For II, III and IV, the slope is constant for $\theta$>100$^\circ$M. Therefore, for wood
products under isothermal conditions, the mass transfer equation (equation 2.24) can be reduced to

\[ \dot{m}'' = -D'_m \nabla M \quad (2.25) \]

In Eq. 2.25, \( D'_m \) is the coefficient of moisture diffusion, similar to the coefficient of thermal diffusivity in Fourier's law.

For nonisothermal moisture movement, the moisture content is not the proper driving force. Several models can be found in the literature to describe nonisothermal moisture transfer. The next paragraph is an extensive presentation of different authors’ work.

2.3.3. Nonisothermal moisture movement models

As shown earlier, the temperature gradient induces a moisture migration and vice-versa. The most common approach to model this effect is to express the mass flux as the sum of the moisture movement due to the concentration (or a vapor-pressure) gradient and the moisture movement due to the temperature gradient. This method has two severe limitations. First, two diffusion coefficients are required, one for the concentration gradient and one for the temperature gradient; these are hardly ever found in the literature. Secondly, this method does not take into account the coupled effect between the two transfers, since they are
assumed to be separate and independent. This coupled effect exists because of the evaporation/condensation effect, always present in hygroscopic materials (see §2.1.2).

The most convenient way to express the nonisothermal moisture transfer would be to find a driving force (gradient of a thermodynamic property) that would take into account the two effects, like Luikov's mass potential. Because of the Soret effect, the gradient of concentration and vapor pressure cannot be used alone as a driving force for Fick's law. Only two driving forces are considered in the literature: the gradient of activated moisture molecules and the gradient of chemical potential.

2.3.3.1. Activated moisture molecules gradient

Skaar and Siau (1981) proposed an equation for nonisothermal moisture movement, based upon a gradient of activated moisture molecules. This model is applicable only for transverse diffusion. Fick's first law is modified to the form

\[ J = -K_M^* \frac{dM^*}{dx} \]  

(2.26)

where \( K_M^* \) is the coefficient for diffusion of activated moisture molecules and \( M^* \) is the content of activated moisture molecules in the wood based on oven dry weight. This result can be calculated from the Boltzmann distribution as
where \( E_b \) is the activation energy, as defined in §2.2.2. The activated moisture content \( M^* \) is a function of both the moisture content (\( M \)) and the temperature (\( T \)). Therefore, the gradient may be evaluated as

\[
\frac{dM^*}{dx} = \exp \left( \frac{E_b}{RT} \right) \left( \frac{E_b}{RT} \frac{dT}{dx} \right) \left( 1 - \frac{M}{RT} \frac{\partial E_b}{\partial M} \right) \exp \left( -\frac{E_b}{RT} \right) \frac{dM}{dx}
\]

(2.28)

The partial derivatives are evaluated assuming that \( E_b \) is independent of \( T \). The symbol \( E_b \) was defined in equation 2.7 as \( E_b = 9200 - 70M \). Therefore, equation 2.28 can be written as

\[
J = -K_m \left[ \left( \frac{M}{RT + 70M} \right) \left( \frac{9200 - 70M}{T} \right) \frac{dT}{dx} \frac{dM}{dx} \right]
\]

where

\[
K = \frac{RT \cdot 70M}{RT} \exp \left( -\frac{E_b}{RT} \right)
\]

(2.29)

The quantity \( K_m \) can be expressed in terms of moisture content and temperature, as shown by Siau and Jin (1985), as

\[
K_m = \frac{0.007 G \rho_w}{(1 - \sqrt{V_o})(1 - V_o)} \exp \left( \frac{-9200 - 70M}{RT} \right)
\]

(2.30)
where \( G \) is the specific gravity of wood, \( \rho_w \) is the normal density of water and \( V_a \) is the porosity of wood.

Equation 2.29 was used by Siau and Babiak (1983) to analyze the results of a series of steady-state nonisothermal experiments through a 4.74 cm thick specimen of *Pinus strobus*. Four experiments were conducted under varying conditions. The cold surface of the specimen was always maintained at 35°C and a relative humidity of 69 per cent. The warm side of the specimen was maintained at 70°C for all tests with relative humidities of 61 per cent, 47 per cent, 35 per cent and 8 per cent. Table 2.2 gives a summary of experimental and theoretical fluxes.

<table>
<thead>
<tr>
<th>Cold side</th>
<th>Hot side</th>
<th>( J_{\text{exp}} )</th>
<th>( J_{\text{theo}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH(_C)</td>
<td>RH(_H)</td>
<td>T(_C)</td>
<td>T(_H)</td>
</tr>
<tr>
<td>69%</td>
<td>35°C</td>
<td>61%</td>
<td>70°C</td>
</tr>
<tr>
<td>69%</td>
<td>35°C</td>
<td>47%</td>
<td>70°C</td>
</tr>
<tr>
<td>69%</td>
<td>35°C</td>
<td>35%</td>
<td>70°C</td>
</tr>
<tr>
<td>69%</td>
<td>35°C</td>
<td>8%</td>
<td>70°C</td>
</tr>
</tbody>
</table>

All fluxes are in \( 10^3 \, \text{g/cm}^2\cdot\text{s} \); A positive flux indicates flow from the hot side to the cold side.

The authors used these data to assert that neither the moisture content gradient nor the vapor pressure gradient alone can explain the observed results. The moisture content is always higher on the cold side, which would result in positive fluxes for all four experiments. If vapor pressure gradient was the only driving force responsible for the moisture movement, the first three experiments would have a negative flux. However, the combination of
moisture content gradient and thermal gradient gives a relatively good agreement between the experimental and theoretical fluxes, as shown in Table 2.2.

2.3.3.2. Chemical potential gradient

Siau’s model

The chemical potential was proposed as a driving force by Kawai et al. (1978) to model bound water movement in isothermal drying. The chemical potential is defined in Eq 2.9. An alternative to the nonisothermal moisture transfer equation (Eq 2.26) was proposed by Siau (1983), based on a gradient of chemical potential. Fick’s first law was modified as

\[ J = -K_\mu \frac{d\mu}{dx} \]  

(2.31)

where \( K_\mu \) is the coefficient of diffusion, based on the chemical potential \( \mu \) of the water vapor. Since the chemical potential varies with both temperature \( T \) and relative humidity \( M \), equation 2.31 can be rewritten as

\[ J = -K_\mu \left[ \frac{\partial \mu}{\partial T} \frac{dT}{dx} + \frac{\partial \mu}{\partial M} \frac{dM}{dx} \right] \]  

(2.32)

Siau claims that the coefficient \( K_\mu \) can be expressed in terms of \( K_M \), which can be expressed in terms of moisture content and temperature (equation 2.30) by
The last term, \( \frac{\partial M}{\partial h} \) can be evaluated from the sorption isotherm.

The definition of chemical potential (equation 2.10) is used to evaluate the derivatives,

\[
\left( \frac{\partial h}{\partial \mu} \right)_r = \frac{h}{RT}
\]

\[
\left( \frac{\partial \mu}{\partial T} \right)_M = \frac{d\mu^m}{dT} + RT \left( \frac{\partial \ln h/100}{\partial T} \right)_M + R \ln \left( \frac{h}{100} \right)
\]

According to Skaar, the second term of \( \frac{\partial \mu}{\partial T} \) may be replaced by \( E_L/T \) where \( E_L \) represents the difference between the molar heat of vaporization of bound water and that of free water, \( E_0 \). Siau evaluated this difference as \( E_L = 6000 \exp(-0.16 M) \).

The first term was evaluated from Heimburg’s data as

\[
\frac{d\mu^m}{dT} = 10.19 \cdot 0.077(T-249)
\]

Finally, Eq 2.31 may be rewritten as

\[
J = -K_M \left[ \frac{h}{RT} \left( \frac{\partial M}{\partial h} \left( \frac{d\mu^m}{dT} + \frac{E_L}{T} \cdot R \ln h/100 \right) \frac{dT}{dx} + \frac{dM}{dx} \right) \right]
\]
This final equation is similar to equation 2.29, which was defined using the gradient in activated moisture molecules. Only the two multipliers of \( \frac{dT}{dx} \), designated by Siau as \( \frac{dM}{dx} \) for the activated molecule model and \( \frac{dM}{dx} \) for the chemical potential formulation, are slightly different. Siau compared the two terms using data from the Wood Handbook (US DA, 1955). The term \( \frac{dM}{dx} \) is higher at low relative humidity and lower at high relative humidities. The two functions become equal at \( h = 53 \) per cent, as shown in Fig. 2.14.

Recently, Siau and Avramidis (1993) published results from a series of nonisothermal tests, compared with two theoretical models: (1) based on a gradient of activated moisture molecules (equation 2.29) and (2) based on a gradient of chemical potential (Eq 2.36). Table 2.3 gives a summary of the average conditions on the cool surface of the specimen for the five series.
Table 2.3. Summary of the average conditions on the cool surface of the specimen in the nonisothermal experiments. Adapted from Siau and Avramidis (1993).

<table>
<thead>
<tr>
<th>Series</th>
<th>RH&lt;sub&gt;c&lt;/sub&gt;, %</th>
<th>T&lt;sub&gt;c&lt;/sub&gt;, °C</th>
<th>RH&lt;sub&gt;b&lt;/sub&gt;, %</th>
<th>T&lt;sub&gt;b&lt;/sub&gt;, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42</td>
<td>29</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>B</td>
<td>45</td>
<td>29</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>C</td>
<td>50</td>
<td>29</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>D</td>
<td>45</td>
<td>37</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>E</td>
<td>67</td>
<td>37</td>
<td>10</td>
<td>70</td>
</tr>
</tbody>
</table>

Figure 2.15. Experimental and theoretical fluxes vs. Equilibrium moisture content on the warm surface of the specimen for experiments of series A, B, C, D and E. Adapted from Siau and Avramidis (1993).
The temperature on the warm side was maintained at 70°C. The first experiments of each series were performed at a low relative humidity RH\textsubscript{a} of about 10 per cent. Each subsequent experiment was done at progressively higher values of RH\textsubscript{a} to a maximum of 47 to 62 per cent, with an increasingly higher equilibrium moisture content M\textsubscript{w}.

Both of the theoretical models used give reasonable agreement with the experimental data. A qualitative comparison of the graphs shows that equation 2.29 tends to fit the experimental points relatively well at the lower values of M\textsubscript{w}, while the thermodynamic model, equation 2.36, gives a poorer fit. As M\textsubscript{w} increases, equation 2.36 fits the experimental data better than equation 2.29.

Siau and Avramidis (1993) then calculated the average sum of squares of the deviation between the theoretical and the experimental fluxes to compare quantitatively the two models. They concluded from this calculation that the thermodynamic model, based on the gradient of chemical potential, fits the experimental data better than the model based on the activated moisture molecules.

**Stanish's model**

Stanish (1986) developed an original mathematical formulation to model moisture transport through wood, pointing out the fact that since the bound water and the water vapor are in equilibrium, the two phases have the same chemical potential. He expressed the mass moisture flux as the sum of the bound water diffusion flux and the water vapor diffusion flux.
\[ J = \dot{m}_v + \dot{m}_b \]  

(2.37)

In Eq. 2.37, \( m_v \) is the molar flux of water vapor through the gas phase and \( m_b \) is the flux of bound water through the cell matrix. The bound water flux is assumed to be directly proportional to the gradient in the chemical potential of the bound water.

\[ \dot{m}_b = - D_v (1 \cdot e) \frac{d\mu_b}{dx} \]  

(2.38)

In Eq. 2.38, \( e \) is the void fraction of wood. Since thermodynamic equilibrium exists between the two phases of water, the chemical potential of the bound water is equal to the chemical potential of the water vapor (i.e. \( \mu_v = \mu_b \)). Using the Gibbs-Duhem relationship for gases (\( M_w d\mu_v = - S \frac{dT}{dx} + V \frac{dP}{dx} \)), equation 2.38 can be rewritten as

\[ \dot{m}_b = - D_v \frac{(1 - e)}{M_w} \left[ \frac{S}{d\mu_v} \frac{RT}{dx} \frac{dP}{dx} \right] \]  

(2.39)

where \( S \) is the molar entropy, \( V \) the molar volume of the gas (assumed ideal), \( R \) the gas constant, \( M_w \) the molar weight of water and \( P \) the water vapor pressure. Stanish derived the entropy coefficient using the fundamental thermodynamic relationship, and values found in the literature. Assuming a constant heat capacity (\( C_p \)), the absolute \( S \) can be expressed as

\[ S = 187 + C_p \ln \frac{T}{298.15} - R \ln \frac{P}{101325} \]  

(kcal/kgK)  

(2.40)
From equation 2.39 and equation 2.40, the flux of bound water only can be expressed as

$$\dot{m}_b = - D_w \frac{(1 - \epsilon)}{M_w} \left[ \left( 187 \cdot C_p \ln \frac{T}{298.15} - R \ln \frac{P}{101325} \right) \frac{dT}{dx} \cdot \frac{RT}{P} \frac{dP}{dx} \right]$$  \hspace{1cm} (2.41)$$

in terms of temperature and vapor pressure.

Stanish expressed the diffusion of water vapor through wood using Fick’s first law as

$$\dot{m}_v = -1.21 \times 10^4 \frac{M_w \alpha T^{0.75}}{R(1 - \frac{P}{P_{\text{total}}})} \frac{d(P/P_{\text{total}})}{dx}$$  \hspace{1cm} (2.42)$$

where $\alpha$ is an attenuation factor which accounts for hindrance of diffusion due to wood structure and porosity and $P_{\text{total}}$ is the total gas pressure.

Finally, the total moisture flux on a mass basis can be expressed by combining equation 2.37, equation 2.41, and equation 2.42 which gives

$$J = -1.21 \times 10^4 \frac{M_w \alpha T^{0.75}}{R(1 - \frac{P}{P_{\text{total}}})} \frac{d(P/P_{\text{total}})}{dx}$$

$$- D_w \frac{(1 - \epsilon)}{M_w} \left[ \left( 187 \cdot C_p \ln \frac{T}{298.15} - R \ln \frac{P}{101325} \right) \frac{dT}{dx} \cdot \frac{RT}{P} \frac{dP}{dx} \right]$$  \hspace{1cm} (2.43)$$

Stanish notes that, unlike the other models (equation 2.29 and equation 2.36), equation 2.43 contains no terms related to the bound water sorption behavior. Temperature and vapor pressure are the only variables of the system. For the common case of $P_{\text{total}} = 101325$ Pa, equation 2.43 can be simplified to
\[ J = - \left[ D_v D_b \left( \frac{462 T}{P} \right) \right] \frac{dP}{dx} - D_b \left( \frac{10400 \cdot 1950 \ln \frac{T}{298.15} - 462 \ln \frac{P}{101325}}{101325} \right) \frac{dT}{dx} \]

where

\[ D_b = D_v \left( 1 - e \right) \]

\[ D_v = \frac{2.60 \times 10^{-12} \alpha T^{0.75}}{1 - P/101325} \]

\( D_b \) and \( \alpha \) are the only parameters in this model related to the wood.

In order to validate his model (equation 2.44), Stanish compared it to data from Voigt (1940), Choong (1963) and Siau (1983).

Choong’s experiments were presented in §2.3.1. Four samples of wood with different initial uniform moisture content were subjected to a nonuniform temperature distribution. Because the wood samples were coated with a vapor barrier, the net flux across the sample is zero. In Stanish’s model, in the case where there is no flux of moisture \( (J = 0) \), only the ratio \( \alpha/D_b \) is required to calculate the moisture distribution in the sample. Stanish sought a constant value for this ratio to provide the best agreement with the reported moisture content profile, for all four experiments (Fig. 2.12). Results are shown in Table 2.4.
Table 2.4. Best fit diffusion parameters for the data of Choong (1963), from Stanish (1986)

<table>
<thead>
<tr>
<th>Experiment No</th>
<th>$\alpha/D_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$7.74 \times 10^{11}$</td>
</tr>
<tr>
<td>2</td>
<td>$6.62 \times 10^{11}$</td>
</tr>
<tr>
<td>3</td>
<td>$8.71 \times 10^{11}$</td>
</tr>
<tr>
<td>4</td>
<td>$15.8 \times 10^{11}$</td>
</tr>
</tbody>
</table>

Since $\alpha/D_b$ depends only upon the material of the sample, the values measured should be equal. Because they are very close to each other, Stanish concluded that his model gives a good agreement with experimental data.

Siau and Babiak’s data are presented in §2.3.3.1. Stanish used these data in order to evaluated $\alpha$ and $D_b$ individually, since they are both needed to calculate the moisture flux. Knowing the experimental conditions for the tests and the measured values for the moisture fluxes, Stanish expressed equation 2.44 as $D_b = f(\alpha)$ as follows,

$$D_b = \frac{-1}{B \frac{dP}{dx} - C \frac{dT}{dx} + J \left( A \frac{dP}{dx} \right)}$$

where

$$A = \frac{2.60 \times 10^{-12} T^{0.75}}{1 - P/101325}$$

$$B = \frac{462 T}{P}$$

$$C = 10400 \times 1950 \ln \frac{T}{298.15} - 462 \ln \frac{P}{101325}$$

For each of the four experiments, $J$, $T$, $P$, $dP/dx$, and $dT/dx$ are known, as shown in table 2.2. The only two parameters left are $\alpha$ and $D_b$. Since the same wood specimen was used
for all four experiments, a convenient test to validate equation 2.45 is whether or not consistent values for $a$ and $D_b$ can be found for which the theoretical solutions agree with all four sets of experimental data. The value of $D_b$ from equation 2.45 is plotted for various values of $a$, for each of the four experiments by Siau and Babiak. Figure 2.16 represents the bound water diffusion coefficients vs. the vapor attenuation factors. Each curve represents a pair of $a$ and $D_b$ for which the solution of the governing equation agrees with the experimental data. All four curves intersect nearly at a single point, as expected for experiments using the same wood sample assuming that neither $a$ nor $D_b$ are functions of moisture content, which is not the case. They could also depend on temperature, since the temperature gradient is the same for all four experiments.

In conclusion, this approach used by Stanish is attractive because the chemical potential expression (equation 2.44), developed using fundamental thermodynamics, does not require
quantitative bound water sorption information. Given the appropriate diffusion parameters ($\alpha$ and $D_b$), the moisture fluxes can be calculated only from the temperature and relative humidity at each end of the specimen. The second contribution of this approach is to model both bound water diffusion and water vapor diffusion as two different mechanisms in the overall transfer. However, this model requires the knowledge of two parameters: $\alpha$, the attenuation factor for water vapor diffusion and $D_b$, the bound water diffusion coefficient. Stanish used the only data available to evaluate them as the best constant value that fits the experimental data. However, a constant value of $D_b$ does not predict higher transfer rates in wetter material (wood), as is commonly observed. Therefore, additional experiments measuring the overall moisture flux are needed for further confirmation of this theory.

**Thomas' model**

The proposed new theory is based on using the gradient of the chemical potential of water as the driving force and accounting for both bound and vapor diffusion. Stanish models (1986) the bound water transfer using a gradient in chemical potential and the vapor transfer rate with a gradient in partial pressure of water. A necessary condition for equilibrium between the three phases of water (bound, free and vapor) in a nonisothermal system is the equality of the chemical potential of water. Consequently, the local gradient of the chemical potential is the same for all phases. Vapor pressure, temperature and moisture concentration gradients are inherently taken into account.
The total moisture flux is expressed as the sum of the bound water diffusion flux and the vapor diffusion flux, as expressed in Eq. 2.37.

Thomas' model differs from Stanish's model in the expression of the bound water and the vapor diffusion fluxes. The bound water diffusion is assumed to be proportional to the gradient in the chemical potential of bound water.

\[ \frac{m_b}{\partial x} = - \frac{C_b D_b}{RT} \cdot \frac{\partial \mu_b}{\partial x} \] (2.46)

where \( D_b \) is the diffusion coefficient of the bound phase, \( C_b \) is the concentration, \( R \) is the universal gas constant.

Similarly, the moisture flux of vapor is expressed as

\[ \frac{m_v}{\partial x} = - \alpha \frac{C_v D_v}{RT} \left( \frac{P}{P_{ideal}} \right) \cdot \frac{\partial \mu_v}{\partial x} \] (2.47)

where \( D_v \) is the diffusivity for water in air and \( \alpha \) is a parameter that accounts for the material porosity and the tortuosity of the air path.

A necessary condition for the equilibrium between the two phases is the equality of the chemical potential.

\[ \mu_v = \mu_b = h - Ts \] (2.48)

where \( h \) is the enthalpy of water and \( s \) is the entropy of water.
Using thermodynamic relationships to express $\mu$ in terms of vapor pressure $P$ and temperature $T$, Eq. 2.48 gives

$$d\mu = \frac{R}{P} dP \cdot s dT \quad (2.49)$$

The concentration $C_b$ and $C_v$ are expressed as follows

$$C_b = \frac{\rho_b}{M_w} = \frac{\gamma \rho_d}{M_w}$$
$$C_v = \frac{P}{R T} \quad (2.50)$$

where $\gamma$ is the sorption isotherm, $\rho_d$ is the dry weight of the material and $M_w$ is the molecular weight of water.

Combining Eqs. 2.46, 2.47, 2.49 and 4.50, the total moisture diffusion is given by

$$m'' = -\left[ \frac{\alpha D_v}{R T \left( \frac{1}{1 - \frac{P}{P_{total}}} \right)} \right] \frac{\partial P}{\partial x} - \left[ \frac{\alpha D_v P}{R T \left( \frac{1}{1 - \frac{P}{P_{total}}} \right)} \right] \frac{s}{R T} \frac{\partial T}{\partial x} \quad (2.51)$$

Equation 2.51 has the requisite form specified by ASHRAE 810-TRP, i.e.,

$$m'' = -\mu \frac{\partial P}{\partial x} - k \frac{\partial T}{\partial x} \quad (2.52)$$

Equation 2.51 requires only two material properties, $\alpha$ and $D_v$. These two properties can be determined using an experimental procedure described by Krus (1992). The basis for this method is that bound-water diffusion in nearly dry materials is negligibly small compared to vapor diffusion and that the parameter $\alpha$ is nearly independent of moisture concentration.
The parameter $\alpha$ can be calculated from measurements of moisture transfer rates and conditions in the two chambers during isothermal tests with a very low relative humidity. With $\alpha$ known, measurements at higher relative humidities give $D_0$ as a function of the moisture content in the material.

This model needs to be validated by comparing results with experimental data. This validation is the object of Chapter 4.

2.4. Conclusion

The objective of this chapter was to present an extensive literature review on the different models to describe moisture diffusion through capillary-porous materials for both isothermal and nonisothermal conditions. Among the different models, several of them are attractive such as Siau’s thermodynamic model and Stanish’s model. However, each one needs further experimental investigations to be either validated or refuted.

An experimental apparatus was developed by R. Crimm (1991) and R. Mosier (1994) to collect moisture diffusion data through a wood sample. This apparatus will allow more data to be taken than the few examples found in the literature. The next chapter will describe this apparatus, as well as the modifications that were implemented to improve it.
CHAPTER 3

Experimental Apparatus and Procedure

An experimental apparatus was constructed to measure moisture transfer through building material samples. The main objective of the apparatus is to measure the moisture flux with both humidity and temperature gradients across the material specimen. The original version of this apparatus was designed and built by Crimm (1992) and implemented by Mosier (1994). It is a unique alternative to the standard "cup" method, which is usually used to measure moisture diffusion. The standard methods are detailed in Mosier's thesis (1994); the cup method will be briefly recalled in the first section.

The experimental apparatus was modified to satisfy two objectives: increase the operational limits and reduce the time required to measure moisture diffusion. A new apparatus was built from Crimm's design to improve its characteristics (control and range). This apparatus will be described in the second section. The third and fourth sections will explain the temperature and the relative humidity control of the apparatus. Finally, the last section will describe the experimental procedure and the method for collecting data in order to measure the moisture transfer rate through a test specimen.
3.1. Standard test method

The American Society of Testing and Materials (ASTM, 1988) describes a standard method for testing the moisture permeability of porous material. This method is also referred to as the cup method. The tests are conducted under isothermal conditions, and the relative humidity is controlled by saturated salt-in-water solutions. Figure 3.1 is an example of the experimental apparatus. The test chamber (1) contains a test dish, also called the “cup” (2) and a test specimen (3), sealed in the test dish with wax. The relative humidity is controlled in the cup side with a salt solution (4) placed in the cup. Another salt solution (5) is placed in the chamber to control the chamber relative humidity.

![Figure 3.1, ASTM Test apparatus.](image)

Many authors used the cup method or modified cup method to collect data on moisture diffusion. However, this method has several strong limitations. The first problem
is the use of a stagnant salt solution. Depending on the salt solution used, several different humidities can be maintained above the salt solution container. Therefore, the operation range is limited to certain setpoints. Moreover, salts tend to migrate toward the specimen surface, which can affect the moisture diffusion properties. Salts can also adversely affect the reading of the instrument used to measure the relative humidity. The second problem is the stagnant atmosphere in the chamber and the cup. Stagnant boundary-layers develop and create relatively large convective resistances at the surface of the specimen which affect the moisture transfer rate. Therefore it is difficult to account for the convective coefficients in determining the permeance of the test material.

Crimm (1992) designed an apparatus that operates under nonisothermal conditions and eliminates the use of the salt solution to control the relative humidity. The current apparatus is described in the next section. It includes many modifications that were required to increase the range of utilization and the control quality.

### 3.2. Description of the apparatus

The experimental apparatus consists of a wood-based specimen sealed between two environmental chambers, each with its own temperature and humidity control system. Air flow is circulated on both side of the specimen. To maintain the desired humidity in a chamber, this air flow is diverted either through a tube of distilled water to increase humidity or through a tube of desiccant to lower the humidity in the chamber. Likewise, flow passes
through a heat exchanger system to control the chamber temperature. An overall schematic of the environmental chamber is shown in Fig. 3.2. Since the setup is similar for both chambers, only one is represented in the figure.

Figure 3.2. Overall Schematic of the experimental apparatus.

Figure 3.3 is a picture of the experimental apparatus. The two experimental chambers, made of brass, with the test specimen in between, are on the right. They are supported on a metal frame by four insulating nylon rods. The chambers are usually covered by 1-in.-thick insulation. At their left stand the four conditioning tubes -- one desiccant tube and one bubble tube for each chamber. The stepper motors that control the flow in the
conditioning tubes are on the middle shelf, under the tubes. On the top shelf are the two dewpoint hygrometers (General Eastern models Hygro M1 and 1200 APS) and the PID controller (Eurotherm). The pumps are on the lower shelf which is separated from the structure to avoid vibrations. One pump is used for the chamber air circulation and the other is for the cooling circuit that can be seen around the chambers. The constant temperature bath for the bottom chamber is on the far right.

Figure 3.3. Picture of the experimental apparatus.

3.2.1. Test specimen

The test specimen consists of a circular board of the material sample --oriented strand
board (OSB) for this study -- mounted in an acrylic ring and sealed with wax. Figure 3.4 is an illustration of the specimen and the mounted ring. This setup allows the wood sample to expand and contract with variations in humidity and prevent flanking leakage. It is critical that the moisture diffuse only through the wood specimen for the accuracy of data.

![Figure 3.4. Test specimen and mounting ring.](image)

3.2.2. Environmental chambers

Each environmental chamber is fabricated in brass. The flanges and the top, made of %-in.-thick brass are respectively of 18 and 22 in. diameter. The chamber height, fabricated from a 1/16 in. thick brass sheet is 6 in. These three parts were joined with 955 alloy solder to avoid any leakage in the chambers.

The ring holder for the test specimen is fastened between the two environmental chambers with 16 bolts equally spaced. A polymeric gasket is placed between the sample holder and each chamber, to prevent leakage.
3.2.3. Instrumentation

Three parameters are critical in this apparatus and required adequate measurement: temperature, pressure and relative humidity.

Static pressure is measured in the top chamber, and a differential pressure is measured between the two chambers, using two pressure gauges that can be seen in Fig. 3.3. It is critical that the static pressures in each chamber are equal. Otherwise, another moisture transport mechanism (convection) would be induced. However, during operation of the apparatus, pressures remain equalized because of the permeability of the specimen. Since the static pressure on both sides are equal, only the diffusion transfer mechanism is present.

Both temperature and humidity in each chamber are recorded during each run to assure steady conditions. The data acquisition system used is a Hewlett Packard 3852A data acquisition and control unit. This unit can read analog voltage from different instruments and measure temperature using type T thermocouples. It also has general purpose switches which are used to open and close solenoid valves. The system is controlled by a program written in GW-BASIC which runs on an IBM PC computer.

The relative humidity can be measured in each chamber using two instruments. Two film-type relative humidity sensors (Vaisala model HMP230) were purchased to measure both temperature and relative humidity in the chamber. This instrument is highly reliable and it is used for the entire run (several weeks). It is quite precise (RH±1% and T±0.2°C), but requires calibration. The RH sensors are placed directly in the chambers, which is where
the relative humidity has to be measured. It also allows a reduction in the number of fittings in the apparatus which helps to reduce possible leaks. On the other hand, two dew-point hygrometers (General Eastern models 1200 APS and Hygro M1) are used to verify the accuracy of the RH sensor (Vaisala model HMP 230) periodically. They are not used during the entire test because they are not sufficiently reliable. This device is an optical condensation hygrometer which works on the chilled-mirror principle. Air flows over a metallic mirror which is cooled until condensation forms. The temperature of the mirror is recorded and corresponds to the dewpoint temperature. The dew-point temperature is related to the relative humidity by a vapor-pressure correlation.

3.2.4. Chamber air circulation

The objective of this apparatus is to keep temperature and relative humidity as steady as possible to avoid the absorption/desorption hysteresis mechanism in the wood sample, which is critical for the mass balance of the system. Another objective is to force air circulation around the sample to minimize moisture transfer resistance associated with a stagnant boundary-layer at the surface of the specimen.

Two small jets induce mixing in the chambers, as shown in Fig. 3.5. The jets are made of 6.35 mm (¼ inch) copper tube with a 2.08 mm (0.082 inches) diameter nozzle soldered on. The main flow enters the chamber through these jets, creating a swirling flow that leads to excellent mixing, and uniform conditions in the chamber. The turbulence of
the flow reduces the convective coefficient at the specimen surface as well, by creating a turbulent boundary layer.

![Image of environmental chamber air circulation](image)

**Figure 3.5.** Environmental chamber air circulation.

The pump used for the air circulation is a metal bellows type pump (Parker Metal Bellows MB-602) which has an extremely low leakage rate. The pump has two separate chambers and, therefore, only one pump is needed to circulate the air in the two environmental chambers.

### 3.3. Temperature control

Each chamber is equipped with its own temperature control system in order to allow two different temperatures on each side of the specimen and therefore create a temperature gradient. The control system, separate for each chamber, is shown in Fig. 3.6.

Temperature control is effected using two different systems. First, the main
circulating flow of the apparatus passes through a counterflow concentric heat exchanger. The heat exchanger is made from two concentric tubes: the main flow passes between the two tubes. The outer tube is made of brass. The inner tube consists of a copper tube which has been modified to increase the exchange surface. The coolant from the constant temperature bath, a mixture of ethylene glycol and water, flows in the inner tube. The temperature in the bath is set to approximately 5°C below the desired temperature in the chamber. After being cooled in the heat exchanger, the main flow is reheated by a resistance heater to the desired temperature. The temperature in the chamber is measured by a type T thermocouple. The Eurotherm temperature controller, using this measured temperature, powers the electric resistance heater.
To improve the temperature control, each chamber is also wrapped by a ¼ in. copper tube containing circulating cooling fluid from the constant temperature bath. This secondary cooling circuit prevents heat exchange between the chamber and the room and therefore the temperature in the chamber is not significantly affected by any temperature variations in the room (such as from the air-conditioning system). The chambers and the heat exchangers are also insulated by a ½-in.-thick foam insulation material.

3.4. Relative Humidity Control

Relative humidity control is also identical for the two chambers. Figure 3.7
represents one relative humidity control system.

![Diagram of relative humidity control system]

Figure 3.7. Relative humidity control system.

The relative humidity is recorded by the computer using a RH sensor. Using the control program which is described in §3.4.1, the computer opens or closes the two motorized valves and the solenoid valve to increase or decrease the relative humidity. To control the relative humidity, the flow goes either to the desiccant tube or to the bubble tube. The conditioning tubes are described in §3.4.2. From Fig. 3.7, it can be seen that the main air flow separates after the pump into two streams. The main part goes to the temperature conditioning system, while a small part goes to the humidity conditioning apparatus. The two stepper motors direct the flow to either the desiccant tube or the bubble tube. The
program is designed so that the flow cannot go through them simultaneously, to avoid premature saturation of the desiccant and simplify the transfer flux measurement procedure described in §3.5. A solenoid valve, upstream of the desiccant tube, avoids a possible counterflow of moisture in the line when the desiccant tube is not in use, which would also use up the desiccant. This valve is a two-position valve (open/closed) which is controlled by the computer and the data acquisition system.

3.4.1. Automated relative humidity control

Relative humidity control is automated for each chamber by a digital feedback control system. The computer algorithm commands the stepper motors and the solenoid valves to achieve and maintain the desired relative humidity in the chambers. The output voltage of the relative humidity probe is recorded by the computer using the data acquisition unit. The RH sensor gives the relative humidity in the chamber directly, as well as the temperature.

The relative humidity measured is compared with the desired value. Depending upon the position of each valve, an adjustment is made to reach this desired setpoint. The control program, CONTROL.BAS is written in GW-Basic. Figure 3.8 is a flowchart describing the logic of the relative humidity control. The listing of the computer code is given in the Appendix.
The controller uses proportional, integral and derivative control. The gains for the proportional, integrative and derivative gains were determined by Mosier (1994) using the trial and error process as 18, 15 and 15 respectively. The size of the step for the valve adjustment is calculated as follows:

\[ N = K_P \left[ E_i \cdot E(K_i - 1) \cdot K_d (E_i - E) \right] \cdot 0.5 \]  

(3.1)

where \( E_i \) is the previous error between the measured RH and the setpoint and \( E \) is the actual error.
3.4.2. Conditioning tubes

Relative humidity is controlled by adding or removing moisture with the conditioning tubes (bubble and desiccant tubes) which are shown in Fig 3.9.

![Conditioning tubes](image)

Figure 3.9. Conditioning tubes.

The four tubes (two for each chambers) are made with acrylic tubes, of 38.1 mm (1½ in.) outside diameter and 25.4 mm (1 in.) inside diameter. To reduce the weight of the tubes, the length of tubing between the metal endcaps is turned to reduce the outside diameter. It is required that the tubes remain in the range of the electronic balance (Mettler):
0-400 g.

The bubble tube is filled with distilled water and is fitted with two 1.59 mm (1/16 in. od) tubes to bubble air through the water and therefore transfer moisture in the circulating air.

The desiccant tube is filled with a drying agent, a synthetic silico aluminate zeolite (David Chemical Molecular Sieve) which absorb moisture. An indicator agent is mixed with the desiccant to show when the desiccant is full of moisture. This indicator is blue when it is dry and turns brown when it is saturated with moisture.

3.5. Test procedure

The apparatus was developed to determine moisture transfer rates through wood-based specimens. The experimental method relies on a steady-state approach, and data can be collected only when steady conditions are attained. When a steady-state is reached, the change of mass of the bubble and desiccant tubes gives the moisture transfer flux across the sample. If the test material is not at steady-state, absorption or desorption of moisture in the specimen would invalidate the mass balance.

Both chambers are equipped with their own humidity control systems. During a test, the humidity is higher on one side than the other. For the purpose of example, consider the top chamber with high humidity and the bottom chamber with low humidity. In that case, moisture will move from the top chamber to the bottom chamber. The top chamber humidity
control will have to provide moisture to maintain the chamber setpoint while the lower chamber humidity control system will have to remove moisture. During steady-state, the source of moisture for the top chamber is the bubble tube and the moisture is removed through the desiccant tube of the bottom chamber. Therefore, it is possible to measure the moisture flux leaving the top chamber and the moisture flux received by the bottom chamber. In the absence of leaks and transient effects, these two fluxes are equal at steady-state.

3.5.1. Leak testing

As shown earlier, the measurement of moisture transfer through the wood sample relies on a measurement of mass change between each chamber. If the chambers or the conditioning circuits contain leaks, ambient moisture may leak in or out of the system, depending upon the conditions. Therefore, if moisture is added or removed from the system, the mass change measured would result in an error on the moisture transfer rate.

A major amount of work was done to minimize leaks from the apparatus, after it was constructed and also between tests. The first and simplest way to test for leaks is to pressurize the entire system and use soap bubbles on every fitting of the apparatus. If air is leaking, the soapy water will bubble and show the presence of a leak. The second method consists of injecting Freon and using a Freon leak detector. This procedure of leak detecting is usually very laborious, but is required before any test in order to have the best possible results.
3.5.2. Measurement

All measurements of the moisture transfer rate through the wood specimen are taken at steady state. Steady state has been reached when the mass change of the conditioning tubes of one chamber is equal to the mass change of the tubes of the other chamber, with an allowance of about 15 percent. Over a period of time, an amount of moisture is added on one side and removed on the other side. The method consists of weighing all four tubes on the Mettler scale over this period of time. The tubes can be disconnected quickly from the line by using quick connectors (Imperial Eastman). This procedure of weighing the tubes takes less than a minute and does not significantly perturb the humidity control. The time interval during each measurement is usually about 24 hours.

3.5.3. Data analysis

The data collected with every measurement consists of the mass of each tube, as well as the date and time of the measurements. The moisture transfer rate depends upon the time interval and the surface of the specimen. It is calculated as

\[ m'' = \frac{\Delta m}{A_s \Delta t} \]  \hspace{1cm} (3.2)

where \( \Delta m \) is the change of mass in the conditioning tubes in one chamber, \( A_s \) is the specimen surface (0.146 m\(^2\)) and \( \Delta t \) is the time interval. The transfer flux is expressed in kg/m\(^2\)s.
3.6. Conclusion

Measuring moisture transfer rate using this apparatus requires a minimum of effort, once the leak testing is done. The temperature and relative humidity control is automated and the setpoints can be maintained continuously with a small error for weeks. Because of the design (forced air circulation in the chamber), each test can be performed more rapidly than the cup method, though each test still takes about 2 to 3 weeks to complete. This experimental setup also allows the error made in measuring the moisture transfer rate to be independently checked, since two fluxes are calculated. It also shows when steady-state is reached. Once steady-state has been established, the process of collecting data by weighing the four tubes is simple. Thus, a significant amount of data can be collected in a relatively short time interval with this apparatus.
CHAPTER 4

Results and Discussion

The scope of the research includes an enhancement of the experimental apparatus as discussed in Chapter 3, verification of the apparatus operation, and collection of data under both isothermal and non isothermal conditions. As described in the previous chapter, the apparatus gives measurements of moisture transfer through the test specimen over a length of time. All data collected are for an oriented strand board (OSB) test specimen, which consists of a circular disk of 0.4318 m (17 in.) diameter with a surface area of 0.146 m² and a thickness of 6.4 mm (¼ in.).

The first section concerns the apparatus operation. Then, isothermal data will be presented and compared with published data. This step will validate the experimental apparatus. The third section will present nonisothermal data, which would implement the diffusion model theory discussed in Chapter 2.

4.1. Apparatus Operation

The apparatus operation concerns the validity and the accuracy of measured data. In order to collect accurate data, both temperature and humidity need to be controlled at the setpoint with a small error. The control relies on the accuracy of the instrument, as well as
the quality of the controllers.

The apparatus controls relative humidities over an operating range from about 5 per cent to 75 per cent. The operating temperature range is from about 15°C to 50°C. At high relative humidity (>75%) or low temperatures (<15°C), condensation tends to form in the coldest part of the apparatus, i.e., the heat exchanger surface. Condensation in the apparatus invalidates the mass balance and, therefore, the experimental results.

4.1.1. Instrumentation

As shown in Chapter 3, the apparatus relies on temperature control and relative humidity control. For each chamber, the computer reads humidity and temperature from a RH sensor. This device was purchased for purpose of long-term stability and reliability, but it requires periodic recalibration. The calibration was done at the factory, and the precision is ±1% for the relative humidity, in the range 0-90% and ±0.2°C for the temperature.

The RH sensor’s outputs are compared with the dewpoint hygrometer (General Eastern) and a type T thermocouple, in order to check its accuracy. The dewpoint hygrometer is designed on the chilled-mirror principle and, therefore, is an absolute measurement. The type T thermocouple output is recorded by the data acquisition through a thermocouple compensation card. Therefore, calibration is not required for the type T thermocouple either. All four output (2 temperatures and 2 relative humidities) are recorded on the computer through the data acquisition system. The three instruments are placed close
to each other in the room. A fan blows air around the instruments, because both humidity
gauges require air flow to operate properly. Comparison between the two temperatures and
the two relative humidities is shown in Fig. 4.1.

Figure 4.1, Validation of the humidity sensor.

Figure 4.1 shows that, for both temperature and relative humidity, the values given
by the humidity sensor are close to the actual values, given by the thermocouple and the
dewpoint hygrometer (General Eastern ). In fact, the error between the two curves is less
than 1 per cent for the relative humidity and less than 0.2°C for the temperature, which are
the stated precision of the humidity sensor. The humidity sensors are therefore used for every test, because they are more reliable than the dewpoint hygrometers. The precision on the temperature and relative humidity is excellent.

4.1.2. Temperature Control

As emphasized earlier, the temperature and the relative humidity control are critical for the quality of the experimental data. If the control is not good, a steady state is not reached and absorption/desorption will invalidate the data, as shown in §3.5.3.
The apparatus was designed to operate under strong nonisothermal conditions. An example of temperature control is given in Fig. 4.2. Data were recorded for about 2 days, and are shown in (a). A close-up is given in (b), which gives a good indication of the quality of the control. The setpoints are 25°C for the top chamber and 20°C for the bottom chamber.

![Figure 4.2. Temperature control.](image)

The temperature gradient through the wood specimen is 787.4 °C/m.

The temperature control, using the Eurotherm PID controller allows control of the
temperature to within ±0.05°C of the setpoint, which is better than the precision of the Vaisala. The temperature control is excellent.

4.1.3. Relative Humidity Control

The relative humidity control quality is shown in Fig. 4.3. The data come from the

(a)

(b)

Figure 4.3. Relative humidity control.
The apparatus is shown to control the relative humidity within ±0.2 per cent of the setpoint, which is better than the precision of the humidity sensor.

4.2. Isothermal tests

The scope of this research includes enhancement and calibration of the new apparatus, verification of measurements and a series of isothermal and nonisothermal tests. The verification of results is done by comparing experimental data to published data, for isothermal conditions. Several nonisothermal tests were performed to support the discussion on nonisothermal moisture diffusion theories.

A series of tests were conducted to validate the experimental data given by the new apparatus. Experimental conditions are given in Table 4.1.

<table>
<thead>
<tr>
<th>Test #</th>
<th>RHᵢ(%)</th>
<th>Tᵢ(°C)</th>
<th>RHₑ(%)</th>
<th>Tₑ(°C)</th>
<th>moisture flux (kg/m²s)</th>
<th>St. dev (kg/m²s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>43.2</td>
<td>24</td>
<td>32.8</td>
<td>24</td>
<td>6.03 10⁻³</td>
<td>1.06 10⁻³</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
<td>24°C</td>
<td>43</td>
<td>24°C</td>
<td>5.76 10⁻³</td>
<td>0.64 10⁻³</td>
</tr>
<tr>
<td>3</td>
<td>43</td>
<td>24°C</td>
<td>58</td>
<td>24°C</td>
<td>5.26 10⁻³</td>
<td>0.92 10⁻³</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>24°C</td>
<td>25</td>
<td>24°C</td>
<td>2.03 10⁻³</td>
<td>0.36 10⁻³</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>24°C</td>
<td>15</td>
<td>24°C</td>
<td>3.35 10⁻³</td>
<td>0.01 10⁻³</td>
</tr>
<tr>
<td>10</td>
<td>65</td>
<td>24°C</td>
<td>55</td>
<td>24°C</td>
<td>4.47 10⁻³</td>
<td>0.64 10⁻³</td>
</tr>
</tbody>
</table>
4.2.1 Validation of the experimental apparatus

Measurements

Once steady state is reached, the mass flux is measured over a period of time for each test. After a week, the moisture transfer is measured every 24 hours for 6 more days. The results of these measurements are shown in Fig. 4.4.

![Figure 4.4. Moisture transfer fluxes measured for test#6.](image)

First, we can note that the two fluxes are not equal: the mass balance change of the conditioning tubes of the bottom chamber is not equal to the mass change for the top chamber.

Errors on the calculation of the moisture flux (Eq. 3.2) can come from error measuring the weight of the tubes and the time interval. Every 24 hours, the mass change of the tube is about 0.5 g. The precision on the sum of the weight of two tubes using the scale is about 0.002 g. Therefore, the measurement uncertainty on the moisture flux resulting from
the scale is of about 0.5 per cent. Similarly, the measurement uncertainty on the time
interval is of about 1 min. The resulting error on the moisture flux is of about 1.6 per cent.

The error, calculated using the mean flux as the reference, is between 6.4 per cent and
28.8 per cent. It is higher than the error made because of the precision of the measurements.
Two hypotheses can be formulated for the cause of the error on the mass balance: (1) the
steady state has not been reached and the absorption/desorption mechanisms invalidate the
mass balance, or (2) leaks are significant. Condensation is not really a concern for these
tests, because of the range of operation of the apparatus.

The first possible source of error is reduced to a minimum by taking data over a long
period of time. First, the time allowed to reach steady state is about a week. Secondly, data
are taken once (sometimes twice) a day. In 24 hours, the absorption or/and desorption
phenomena which occur because of the oscillation in temperature and humidity (see Fig 4.2
and 4.3) are smoothed. Unfortunately, there is no known way to quantify the error resulting
from absorption and desorption.

During all these tests, leaks were always a major concern. Leak testing was
performed before each test and corrected. However, after each test, some leaks are
inevitable in the apparatus. They probably result from the vibration of the pump and failures
in the solder. For example, the chambers had to be fixed (resoldered on the joints) three
times. The mass flux of moisture leaving or received by the apparatus depends strongly upon
the experimental conditions and the room conditions. It is therefore impossible to quantify
these leaks.
Influence of gravity

An important concern with the design of this apparatus is that the sample is mounted in a horizontal plane. As pointed out in Chapter 2, gravity induces a transport mechanism of moisture through the sample. The purpose of test 3 was to evaluate the importance of gravity on moisture transfer. For test 3, conditions are similar to test 2, but opposite (see Table 4.1). The moisture flux in test 2 is in the direction of gravity, whereas the flux in test 3 is opposite to the direction of gravity. Therefore, the flux measured in test 2 is expected to be higher than the flux in test 3. Results are given in table 4.2.

Table 4.2. Influence of gravity on the moisture flux.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Moisture flux (kg/sm²)</th>
<th>St. dev. (kg/sm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5.76 10⁻⁸</td>
<td>0.64 10⁻⁸</td>
</tr>
<tr>
<td>3</td>
<td>5.26 10⁻⁸</td>
<td>0.92 10⁻⁸</td>
</tr>
</tbody>
</table>

As expected, the moisture flux is higher when it is in the direction of gravity. However, because of the experimental uncertainty, nothing can be said about the importance of the direction of the flux. Moreover, gravity alone cannot explain this phenomenon. As pointed out by Mosier (1994) in his data reduction, the mass transfer coefficients are found to be 0.0152 and 0.0142 m/s for the bottom and top chamber respectively for ½ in. thick fiberboard. Therefore, the system is not perfectly symmetrical.

To avoid the calculation of the resistance transfer coefficients (which depends upon
the driving force considered), further results will be expressed only in terms of the moisture flux. Conditions will be set so that moisture diffuses from the top chamber to the bottom chamber, which is the way it is set in all other measuring methods including the cup method.

4.2.2. Comparison with published data

According to the proposal for this research, the purpose of one of the first tests was to validate the apparatus. Test 3 was set so that the moisture flux measured can be compared to Dahl, Kuehn and Ramsey’s (1995) experiments. Using the “cup” method (saturated salt solutions), they measured the moisture flux for ¼-in.-thick OSB in various configurations. One test was performed with the following conditions: RH₁=58%, RH₂=43%, T₁=24.3°C and T₂=24°C. The experimental conditions are nonisothermal, but the gradient in temperature is weak. Results should not differ much from test 3.

The moisture flux measured by Dahl, Kuehn and Ramsey is m‴=5.70 × 10⁻⁸ kg/m².s. Test 3 gave m‴=5.76 ±0.64 × 10⁻⁸ kg/m².s. The effect of the temperature gradient is not strong and both sets of data compare well.

The second set of measurements under isothermal conditions was performed to produce the permeability curve μ = f(RH). These data are compared to data obtained at the National Institute of Standard and Technology (NIST) which measured the moisture permeability of various wood specimen under isothermal conditions (Burch, 1992).
Figure 4.5 is a plot of the data obtained for various isothermal conditions (see Table 4.1) and the data reported by NIST, for OSB at 24°C. The permeability is calculated by dividing the measured moisture flux by the vapor pressure gradient.

As emphasized earlier, the limits of operation of the experimental apparatus do not allow high relative humidity without condensation problems. That is the reason why the top of the curve cannot be verified. Otherwise, data can be reasonably compared with NIST's data. The moisture transfer flux given correspond to the average moisture flux measured for the two chambers. Standard deviation for each test is given in Table 4.1.

Apparatus operation was verified and data were compared to published data under nonisothermal conditions. The comparison with existing data validated the apparatus.
Nonisothermal tests can be performed with confidence in the quality of the results.

4.3. Nonisothermal tests

As shown in a previous chapter, the apparatus allows tests with a strong temperature gradient. Nonisothermal tests can easily be performed with 5°C temperature difference across the ¼-in.-thick wood sample.

The method used to collect data is the same as for isothermal tests: the four conditioning tubes are weighed over a period of time. Table 4.3 summarizes the nonisothermal tests performed.

Table 4.3. Nonisothermal tests conditions.

<table>
<thead>
<tr>
<th>Test#</th>
<th>Top chamber</th>
<th>Bottom chamber</th>
<th>Moisture flux</th>
<th>St. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (°C)</td>
<td>RH (%)</td>
<td>T (°C)</td>
<td>RH (%)</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>30</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>45</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>25</td>
<td>20</td>
<td>33.3</td>
</tr>
</tbody>
</table>

A positive sign correspond to a moisture flux from the top to the bottom chamber.

These experiments are chosen to test the diffusion model theory. In order to validate a diffusion model, it is necessary to satisfy the null condition: if the gradient of the assumed driving force (concentration, vapor pressure, chemical potential) is set to zero, then the measured flux should vanish. The experimental conditions for these three tests correspond to (4) the equilibrium of vapor pressure, (5) the equilibrium of chemical potential and (7) the
equilibrium of concentration.

An example of measurements is given in Fig. 4.6. Once a steady state has been reached, data are collected every 24 hours, for 10 days. As in Fig 4.4, the two fluxes are not equal. This inequality is also likely to result from some leakage in the system. However, the error between the two measurements is about 33 per cent, which clearly gives indications about the behavior of the moisture flux. As noted earlier, these experiments are designed to test the null condition for different driving forces. These are the worst conditions for the apparatus, since the mass flux measured is expected to be close to zero. Therefore, the error due to leaks is expected to be of significant importance for the mass flux measured, but the data should be close enough to indicate if the null condition is satisfied or not.

![Figure 4.6. Moisture transfer fluxes measured for test 7.](image)

**Equilibrium of concentration**

Test 7 was conducted to verify the importance of the Soret effect. In the literature
(cf Chapter 2), the Soret effect was investigated by the following experiment: a sealed wood sample with initially uniform moisture distribution is subjected to a temperature gradient. Moisture redistributes within the sample, but does not diffuse through the wood, since it is sealed with a moisture-proof barrier. Moreover, because of the experimental method used, only bound water redistribution is taken into account. Since the temperature is lower on one side, condensation is more likely to occur which would increase the concentration of bound water.

Test 7 follows a different approach: conditions in both chambers are set so that the concentration (kg/m³) of water is the same on both sides of the wood specimen. According to published data, the moisture should flow in the direction of decreasing temperature. The experimental moisture flux measured was clearly going in the direction of increasing temperature, with a net value of $2.61 \times 10^{-8} \pm 0.46 \times 10^{-8}$ kg/m²s. This result is in contradiction with the Soret effect as it is usually measured. As pointed out before, test 7 takes into account the diffusion of the 3 phases across the specimen and is not just a redistribution of bound-water. Therefore, it could be possible that each separate phase diffuses in different directions depending upon the experimental conditions; the bulk moisture flux could then be in either direction.

**Equilibrium of vapor pressure**

The purpose of test 4 was to investigate the applicability of the commonly used mass transfer model (i.e. Fick's law based on the vapor pressure gradient). According to this
formulation, if there is no vapor pressure gradient, no mass diffusion should occur.

Experimental conditions were set so that the vapor pressure was 1.268 kPa on both sides of the material tested. Results are given in Table 4.3. During the test, the direction of the moisture transfer was not well defined. For some data, it was going from the bottom chamber to the top chamber while for others the moisture flux was leaving the top chambers. Leaks in the system clearly affect the data and it is impossible to say if the null condition is attained.

Equilibrium of chemical potential

Experimental conditions for Test 5 are chosen so that the chemical potential of water is equal on both sides of the test specimen. This test was performed in order to validate -or refute- the moisture diffusion models based on a chemical potential gradient (see Chapter 2). The moisture flux is measured at $m' = 2.07 \times 10^{-8} \pm 0.91 \times 10^{-8} \text{ kg/m}^2\text{s}$. Despite the importance of leaks, the moisture flux is clearly going from the top chamber to the bottom chamber. These data show that moisture diffusion model based on a chemical potential gradient does not satisfy the necessary null condition under a strong temperature gradient.

4.3. Summary of Results and Recommendations

The objective of the research was to modify and operate an apparatus for the measurement of moisture transfer rate in building materials. The goal was to verify its
operation and to collect data. Moisture transfer rates were obtained for both isothermal and
nonisothermal conditions. Comparison of data measured with the new apparatus to
published data shows a good agreement.

Despite many experimental problems that made the collection of data more difficult
than expected (such as leak problems), the present apparatus is well suited for the acquisition
of large amounts of data. Operating ranges were improved through the use of brass
chambers, with wraparound cooling circuit to prevent heat loss, and through the use of a
highly effective heat exchanger. The temperature and relative humidity control are now
excellent and reliable with the new RH sensors. However, leaks are still a very important
concern with this apparatus, although they were reduced significantly. Between each test,
a laborious leak testing and repairing procedure needs to be performed.
CONCLUSION

This research had two main objectives: the enhancement of the existing experimental apparatus and the implementation of the moisture theory discussion. After introducing the moisture problem for the building industry, a comprehensive discussion of moisture diffusion models for both isothermal and nonisothermal conditions has been presented. Whereas moisture diffusion is well understood under isothermal conditions, many diffusion models exist for both humidity and temperature gradients; but none of them is universally accepted. The literature review focused on potential theories, such as Fick’s first law. The goal of this research was to investigate some of these models and compare them with experimental data.

The apparatus developed in the present research project is an alternative of all the existing moisture permeability measurement techniques. It consists of a test specimen sealed between two environmental chambers, each one with its own temperature and humidity control system. It is capable of maintaining strong temperature and humidity gradients across a circular wood specimen. The advantages of using this method include the absence of salt solutions, mixing in the chamber to assure uniform conditions, and the reduction of the resistance transfer coefficient due to forced convection and turbulence above the specimen surface.
Measures of operational performance have been established. The apparatus is capable of maintaining the temperature within limits of ± 0.05°C and relative humidity within limits of ± 0.2 per cent, in a range of 15-50°C and 5-75 per cent. Validation of the experimental apparatus was done by comparing data collected with published data, under isothermal conditions. Measurement uncertainties account for only about 2 per cent of the error made on the moisture flux. However, leaks can be significant and can account for up to 30 per cent experimental variations. Nonisothermal tests were performed to implement the moisture diffusion model theories. These experiments suggest further investigations in order to find a model that satisfies a necessary condition: when the gradient of the assumed driving force is set to be zero, the measured moisture flux should be zero. Therefore, this study suggests the need for further experimentation to identify the proper driving force.

It would also be interesting to repeat the test showing the Soret effect with different experimental conditions, in order to determine the importance of the Soret effect on moisture diffusion.
REFERENCES


APPENDIX

Control Computer Code

585    ' User program can begin anywhere past this point
587    '-------------------------------------------------------------------------------------
588    ' Edit Setpoints
589    SETPT=.35
590    SETPT2=.45
591    '-------------------------------------------------------------------------------------
592    TIME$="00.00.00"
593    CLS
594    NLOC=1
595    GOSUB 11000    'call subroutine initialize
596    GOSUB 4000    'Calculate initial errors, EK & EKO
597    ON TIMER(20) GOSUB 645
598    TIMER ON
599    REM
600    GOTO 625
601    644    '
602    645    ' MAIN BODY OF PROGRAM
603    646    '-------------------------------------------------------------------------------------
607    648    '
608    650    GOSUB 13000    'call subroutine temperature
609    660    GOSUB 1000    'call subroutine read voltage
610    680    GOSUB 5000    'call subroutine move motors
611    685    EK=EK1
612    686    EKO=EKO1
613    890    GOSUB 12000    'call subroutine print
614    950    IF N=0 THEN GOTO 960 ELSE GOTO 985
615    960    'OPEN "c:\data\test6.DAT" FOR APPEND AS #1
616    978    'PRINT #1,TBOT,DPBOT,100*RHBOT, TTOP,DPTOP,100*RHTOP
617    980    'CLOSE #1
618    985    N=N+1
619    987    IF N=20 THEN N=0
620    990    RETURN
621    998    '
622    999    '-------------------------------------------------------------------------------------
630    1000    'SUBROUTINE READ DEWPOINTER VOLTAGE => DPTOP & DPTOP
631    1001    '-------------------------------------------------------------------------------------
632    1002    '
633    1030    VOLL=0
634    1040    FOR J=1 TO 50
635    1050    S3$="CONFMEAS DCV,205"
636    1060    LEN3=LEN(S3$)
637    1070    CALL IOOUTPUTS(DEV,S3$,LEN3)
638    1080    CALL IOENTER(DEV,V1)
639    1090    VOLL=VOLL+V1
1100 NEXT J
1110 VO1=VOLT1/50
1120 RHBOT =(VO1*20)/100
1200 EK1 = ABS(RHBOT - SETPT)
1300 KP=18
1310 KI=15
1315 KD=15
1330 NSTEP=INT(KP*(EK1-EK+KI*EK+KD*(EK1-EK))+.5)
1340 NSTEP=ABS(NSTEP)
1390 ,
1400 VOLT2=0
1410 FOR I=1 TO 50
1420 S6$="CONFMEAS DCV,207"
1430 LEN6=LEN(S6$)
1440 CALL IOOUTPUTS(DEV,S6$,LEN6)
1450 CALL IOENTER(DEV,V2)
1460 VOLT2=VOLT2+V2
1470 NEXT I
1480 VO2=VOLT2/50
1490 RHTOP=(20*VO2)/100
1500 EKO1=ABS(RHTOP-SETPT2)
1530 NSTEP2=INT(KP*(EKO1-EKO+KI*EKO+KD*(EKO1-EKO))+.5)
1540 NSTEP2=ABS(NSTEP2)
1590 RETURN
1999 ,
3999 '---------------------------------------- +--+ ---
4000 'SUBROUTINE CALCULATE INITIAL ERROR
4001 '----------------------------------------
4002 ,
4010 VOLT1=0
4020 FOR J=1 TO 50
4030 S4$="CONFMEAS DCV,205"
4040 LEN4=LEN(S4$)
4050 CALL IOOUTPUTS(DEV,S4$,LEN4)
4060 CALL IOENTER(DEV,V1)
4070 VOLT1=VOLT1+V1
4080 NEXT J
4090 VO1=VOLT1/50
4095 RHBOT =(VO1*20)/100
4100 EK = ABS(RHBOT - SETPT)
4190 ,
4200 VOLT2=0
4210 FOR I = 1 TO 50
4220 S5$="CONFMEAS DCV,207"
4230 LEN5=LEN(S5$)
4240 CALL IOOUTPUTS(DEV,S5$,LEN5)
4250 CALL IOENTER(DEV,V2)
4260 VOLT2=VOLT2+V2
4270 NEXT I
4280 VO2=VOLT2/50
4285 RHTOP =(VO2*20)/100
4290 EKO=ABS(RHTOP-SETPT2)
4300 RETURN
4998 ,
5000 'suroutine move motor
5001 '------------------------------
5010 IF RHBOT<SETPT THEN GOSUB 5030 ELSE GOTO 5180
5020 GOTO 5330
5030 IF SOLEN=1 THEN GOSUB 5050 ELSE GOSUB 5150
5040 RETURN
5050 IF DESI=1 THEN GOSUB 5070 ELSE GOSUB 5100
5060 RETURN
5070 L=0
5080 GOSUB 6500
5090 RETURN
5100 GOSUB 9000
5110 RETURN
5120 L=1
5130 GOSUB 7500
5140 RETURN
5150 L=1
5160 GOSUB 7500
5170 RETURN
5180 IF RHBOT=SETPT THEN GOTO 5330 ELSE GOSUB 5200
5190 GOTO 5330
5200 IF BUBL=1 THEN GOSUB 5220 ELSE GOSUB 5250
5210 RETURN
5220 L=0
5230 GOSUB 7500
5240 RETURN
5250 IF SOLEN=1 THEN GOSUB 5270 ELSE GOSUB 5300
5260 RETURN
5270 L=1
5280 GOSUB 6500
5290 RETURN
5300 GOSUB 8000
5301 L=1
5302 GOSUB 6500
5310 RETURN
5320 '
5340 IF RHTOP<SETPT2 THEN GOSUB 5360 ELSE GOTO 5510
5350 GOTO 5640
5360 IF SOLEN2=1 THEN GOSUB 5380 ELSE GOSUB 5480
5370 RETURN
5380 IF DESI2=1 THEN GOSUB 5400 ELSE GOSUB 5430
5390 RETURN
5400 L=0
5410 GOSUB 6000
5420 RETURN
5430 GOSUB 9500
5440 RETURN
5450 L=1
5460 GOSUB 7000
5470 RETURN
5480 L=1
5490 GOSUB 7000
5500 RETURN
5510 IF RHTOP=SETPT2 THEN GOTO 5640 ELSE GOSUB 5530
5520 GOTO 5640
5530 IF BUBL2=1 THEN GOSUB 5550 ELSE GOSUB 5580
5540 RETURN
5550 L=0
5560 GOSUB 7000
5570 RETURN
5580 IF SOLEN2=1 THEN GOSUB 5600 ELSE GOSUB 5630
5590 RETURN
5600 L=1
5610 GOSUB 6000
5620 RETURN
5630 GOSUB 8500
5631 L=1
5632 GOSUB 8500
5633 RETURN
6000 ' subroutine move motor A
609 ' subroutine move motor A
6010 ' subroutine move motor A
6011 ' subroutine move motor A
6012 ' subroutine move motor A
6020 IF NA>1500 THEN GOTO 6040
6030 IF L=1 THEN NA=NA+NSTEP2
6040 IF L=0 THEN NA=NA-NSTEP2
6050 DISABLE=2+4+8
6060 PORTB=MODEAB+DISABLE+MODECD
6070 OUT PB,PORTB
6080 IF NSTEP2=0 THEN GOTO 6180
6090 FOR I=1 TO NSTEP2
6100 IF L=0 THEN OUT PA,17
6110 IF L=0 THEN OUT PA,16
6115 IF NA>1500 THEN GOTO 6140
6120 IF L=1 THEN OUT PA,1
6130 IF L=1 THEN OUT PA,0
6140 NEXT I
6150 ENABLE=1+2+4+8
6160 PORTB=MODEAB+ENABLE
6170 OUT PB,PORTB
6180 IF NA<=0 THEN DESI2=0 ELSE DESI2=1
6190 IF NA<0 THEN NA=0
6200 RETURN
6498 ' subroutine motor B
6501 ' subroutine motor B
6502 ' subroutine motor B
6510 IF NB>1500 THEN GOTO 6530
6520 IF L=1 THEN NB=NB+NSTEP
6530 IF L=0 THEN NB=NB-NSTEP
6540 DISABLE=1+4+8
6550 PORTB=MODEAB+DISABLE
6560 OUT PB,PORTB
6570 IF NSTEP=0 THEN GOTO 6670
FOR I=1 TO NSTEP
IF L=0 THEN OUT PA,34
IF L=0 THEN OUT PA,32
IF NB>1500 THEN GOTO 6630
IF L=1 THEN OUT PA,2
IF L=1 THEN OUT PA,0
NEXT I
ENABLE=1+2+4+8
PORTB=MODEAB+ENABLE
OUT PB,PORTB
IF NB<=0 THEN DESI=0 ELSE DESI=1
IF NB<0 THEN NB=0
RETURN

IF NC>1500 THEN GOTO 7030
IF L=1 THEN NC=NC+NSTEP2
IF L=0 THEN NC=NC-NSTEP2
DISABLE=1+2+8
PORTB=MODEAB+DISABLE+MODECD
OUT PB,PORTB
IF NSTEP2=0 THEN GOTO 7170
FOR I=1 TO NSTEP2
IF L=0 THEN OUT PA,68
IF L=0 THEN OUT PA,64
IF NC>1500 THEN GOTO 7130
IF L=1 THEN OUT PA,4
IF L=1 THEN OUT PA,0
NEXT I
ENABLE=1+2+4+8
PORTB=MODEAB+ENABLE+MODECD
OUT PB,PORTB
IF NSTEP=0 THEN GOTO 7670
FOR I=1 TO NSTEP
IF L=0 THEN OUT PA,136
IF L=0 THEN OUT PA,128
7605 IF ND>1500 THEN GOTO 7630
7610 IF L=1 THEN OUT PA, 8
7620 IF L=1 THEN OUT PA, 0
7630 NEXT I
7640 ENABLE=1+2+4+8
7650 PORTB=MODEAB+ENABLE+MODECD
7660 OUT PB, PORTB
7670 IF ND<=0 THEN BUBL=0 ELSE BUBL=1
7680 IF ND<0 THEN ND=0
7690 RETURN
7998
7999 '-------------------------------------------------
8000 'SUBROUTINE OPEN SOLENOID VALVE
8001 '-------------------------------------------------
8010 DEV=709
8020 CALL IOCLEAR(DEV)
8030 S1$=SPACES(25)
8040 S1$="OPEN 500"
8050 LH=LEN(S1$)
8060 CALL IOOUTPUTS(DEV, S1$, LH)
8070 SOLEN=1
8400 RETURN
8498 '
8499 '-------------------------------------------------
8500 ' SUBROUTINE OPEN SOLENOID VALVE 2
8501 '-------------------------------------------------
8520 DEV = 709
8530 CALL IOCLEAR(DEV)
8540 S8$ = SPACES(25)
8550 S8$ = "OPEN 501"
8560 LH = LEN(S8$)
8570 CALL IOOUTPUTS(DEV, S8$, LH)
8580 SOLEN2 = 1
8580 SOLEN2 = 1
8900 RETURN
8997 '
8998 '-------------------------------------------------
8999 'SUBROUTINE CLOSE SOLENOID VALVE
9001 '-------------------------------------------------
9002 '
9005 DEV=709
9010 CALL IOCLEAR(DEV)
9020 S2$=SPACES(25)
9030 S2$="CLOSE 500"
9040 LH=LEN(S2$)
9050 CALL IOOUTPUTS(DEV, S2$, LH)
9060 SOLEN=0
9400 RETURN
9498 '
9499 '-------------------------------------------------
9500 ' SUBROUTINE CLOSE SOLENOID VALVE 2
9501 '-------------------------------------------------
9502 '
9510  DEV = 709
9520  CALL IOCLEAR(DEV)
9530  S9$=SPACES$(25)
9540  S9$="CLOSE 501"
9550  LH=LEN(S9$)
9560  CALL IOOUTPUTS(DEV,S9$,LH)
9570  SOLEN2=0
9580  RETURN
9590  '----------------------------------------
9600  'SUBROUTINE INITIALIZE
9610  '----------------------------------------
9620  '
9630  SOLEN = 1
9640  SOLEN2 = 1
9650  PA=736: PB=740: FC=744: CO=748
9660  OUT CO, 192
9670  OUT PC, 5
9680  'SET FULL OR HALF STEP
9690  MODEAB=0
9700  MODECD = 2^6
9710  NA=0
9720  NB=0
9730  NC=0
9740  ND=0
9750  NSTEP = 0
9760  NSTEP2 = 0
9770  BUBL=0: BUBL2=0
9780  DESI=0: DESI2=0
9790  GOSUB 9000
9800  GOSUB 9500
9810  GOSUB 13000
9820  DISABLE=2+4+8
9830  RETURN
9840  '----------------------------------------
9850  'SUBROUTINE PRINT
9860  '----------------------------------------
9870  '
9880  LOCATE 1,1
9890  PRINT " BUB DES BOT BOT BUB BOT TOP TOP"
9900  PRINT " POS POS T R.H POS POS T R.H"
9910  PRINT"
9920  LOCATE 3+NLOC
9930  PRINT USING"####";ND;
9940  PRINT USING"#####";NB;
9950  'IF SOLEN=1 THEN PRINT " OPEN ";
9960  PRINT USING"#####.##";TBOT;
9970  'IF SOLEN=0 THEN PRINT " CLOSED ";
9980  PRINT USING"#####.##";RHBOT*100;
9990  PRINT "% ";
10000  PRINT USING"#####";NC;
10010  PRINT USING"#####";NA;
10020  'IF SOLEN2=1 THEN PRINT " OPEN ";
10030  PRINT USING"#####.##";TTOP;
10040  '----------------------------------------
' IF SOLEN2=0 THEN PRINT " CLOSED ";
PRINT USING"##.##";RHTOP*100;
PRINT ":
LOCATE 1,1
PRINT" BUB DES BOT BOT BUB DES POS POS T R.H POS POS T R.H
PRINT" POS POS T R.H
NLOC=NLOC+1
IF NLOC=22 THEN NLOC=NLOC-1
RETURN

'---------------------------------------------
' SUBROUTINE TEMPERATURE
'---------------------------------------------

TEMP1=0
FOR J=1 TO 50
S1$="CONFMEAS DCV, 206"
LEN1=LEN(S1$)
CALL IOOUTPUTS(DEV,S1$,LEN1)
CALL IOENTER(DEV,TEM1)
TEMP1=TEMP1+TEM1
NEXT J
TE1=TEMP1/50
TBOT = TE1*20-20

TEMP2=0
FOR I=1 TO 50
S2$="CONFMEAS DCV, 208"
LEN2=LEN(S2$)
CALL IOOUTPUTS(DEV,S2$,LEN2)
CALL IOENTER(DEV,TEM2)
TEMP2=TEMP2+TEM2
NEXT I
TE2=TEMP2/50
TTOP = TE2*20-20
RETURN
The author, Vincent F. Chevrier, was born in Nancy, France on October 11, 1972. He has since lived in Chavigny, a small village in near Nancy.

He received his bachelor's degree in chemical engineering (heat transfer) from the Université de Technologie de Compiègne, France in 1995. During his last year, he took advantage of an exchange program between UTC and Virginia Tech and moved to Blacksburg, VA to be enrolled in the Master of Science program in Mechanical Engineering (heat transfer).

In the immediate future, he plans to move to Pittsburgh, PA to work as a research assistant for the Center for Iron and Steelmaking Research at Carnegie Mellon University. This position is offered by a French steelmaking company, Usinor-Sacilor, and will be validated as his mandatory military service.