ANALYSIS OF THE CONDENSATION PROBLEM ON THE INNER SURFACE OF FULLRIGGAREN’S LARGE VERTICAL WINDOW

Anabel Castro

June 2013

Master’s Thesis in Energy Systems
15 credits
PREFACE

First of all, I would like to thank Professor Taghi Karimipanah, for making possible the realization of this work, both by providing me with this Thesis and helping me in every possible aspect, solving all kind of doubts.

I am also very grateful to Professor Björn Karlsson for his helpful comments and interest in the correct development of my ideas.

I couldn’t forget to especially thank Roland Forsberg, who establishes the contact with Sweco Company, for all his useful advices, provision of material and kindness.
In the same way, I would like to make a special mention for Huijan Chen for guiding me in the building of the model for the software.

Last but not least, I would like to finish thanking my friends and relatives for their support and making this experience unforgettable.
ABSTRACT

This Thesis is focused on the study of the problem of condensation on the inner surface of Fullrigaren building’s large single pane window. This has serious consequences as water on the floor, corrosion or mould growth.

As the climate in Nordic countries is cold for several months a year, windows are a crucial part in building envelopes. Condensation on a window may be suitably discussed only with respect to the climate considered as cold, moderate and warm climates pose different requirements on the windows, and this is why a characterization of Gävle by its climate is necessary.

This Thesis will include the energy analysis of the staircase considered which is required to understand the source of the actual problem. Both heat and moisture transfer will be studied. In this purpose, an IDA model will be built to simulate the conditions throughout the year and hand-made calculations will be done for the average and most critical situations. The results show that condensation will already occur for the monthly average conditions having as an additional problem that if temperature drops below zero it will freeze.

Results will also be compared to an initial installation of a 2 pane window reaching as a conclusion that its original installation would had avoided the problems for most of the time.

The Thesis will end with several proposals posed to solve the problem by either increasing the temperature or reducing the moisture content of the ambient air, and the selection of the best one. The final aim of the Thesis is to achieve an energy efficient window which should provide good lighting during the day and good thermal comfort both during day and night at minimum demand of paid energy. And for this, the selection of the electrically heated window is proposed.

Keywords: dew point, condensation, psychrometric chart, cold climates, window panes, building energy analysis
# TABLE OF CONTENTS

1. INTRODUCTION ........................................................................................................... 3
   1.1 Background ............................................................................................................... 3
   1.2 Problem description ................................................................................................. 4
   1.3 Objectives .............................................................................................................. 6

2. THEORY ....................................................................................................................... 7
   2.1 Main concepts .......................................................................................................... 7
   2.2 Psychrometric chart ............................................................................................... 8
   2.3 Condensation: causes and consequences .............................................................. 11

3. CLIMATIC CONDITIONS ............................................................................................. 15
   3.1 Temperature .......................................................................................................... 16
   3.2 Humidity ............................................................................................................... 17
   3.3 Wind ...................................................................................................................... 18
   3.4 Radiation .............................................................................................................. 19

4. METHOD ..................................................................................................................... 20
   4.1 Description ............................................................................................................. 20
   4.2 IDA model ............................................................................................................ 21
   4.3 Experimental procedure ....................................................................................... 23
   4.4 Glazing type ........................................................................................................ 24

5. ENERGY ANALYSIS ................................................................................................... 28
   Windows and energy conservation ............................................................................. 28
   5.1 Heat transfer ......................................................................................................... 29
      5.1.1 Heat losses ................................................................................................... 30
      5.1.2 Heat gains .................................................................................................. 38
   5.2 Moisture Transfer ............................................................................................... 42

6. RESULTS ..................................................................................................................... 50
   6.1 Hand-made results ............................................................................................... 50
6.2 Results with IDA ................................................................................................. 55

7. ANALYSIS FOR 2 PANE WINDOW CONSIDERATION ........................................ 57

7.1 Hand-made results ............................................................................................ 58
7.2 Results with IDA .............................................................................................. 60
7.3 Considering a triple pane window ...................................................................... 60

8. SOLUTIONS .......................................................................................................... 63

8.1 Increasing temperature ..................................................................................... 63
  8.1.1 Secondary Glazing ...................................................................................... 63
  8.1.2 Electrically heated window pane ............................................................... 65
  8.1.3 Secondary film ........................................................................................... 68
  8.1.4 Considering Emerging Technologies-Building applied Photovoltaics (BAPV) .................................................................................. 71
  8.1.5 Adding a radiator ....................................................................................... 72

8.2 Decreasing air humidity .................................................................................... 74
  8.2.1 Higher ventilation ...................................................................................... 74
  8.2.2 Air-conditioning ....................................................................................... 75
  8.2.3 Condensate trap in aluminum tubes .......................................................... 77

8.3. Selection of the best option ............................................................................ 77

9. DISCUSSION AND CONCLUSIONS .................................................................. 79

REFERENCES ......................................................................................................... 82

APPENDIX ............................................................................................................... 85
# TABLE OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fullriggaren building</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Window to be analyzed</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>CAD dimensions</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Properties of moist air on a psychrometric chart</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>Dry bulb temperature in the psychrometric chart</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Absolute humidity on the psychrometric chart</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>Saturation line screen</td>
<td>9</td>
</tr>
<tr>
<td>8</td>
<td>Relative humidity screen</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>Representation of Wet Bulb Temperature on the psychrometric chart</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>Dew point temperature on the psychrometric chart</td>
<td>10</td>
</tr>
<tr>
<td>11</td>
<td>Representation of precipitation on the psychrometric chart</td>
<td>11</td>
</tr>
<tr>
<td>12</td>
<td>Images of problems caused</td>
<td>13</td>
</tr>
<tr>
<td>13</td>
<td>Effect of moisture on the measured thermal conductivity</td>
<td>14</td>
</tr>
<tr>
<td>14</td>
<td>Annual Temperature profile of Gävle</td>
<td>16</td>
</tr>
<tr>
<td>15</td>
<td>Relative Humidity for Gävle</td>
<td>17</td>
</tr>
<tr>
<td>16</td>
<td>Annual Humidity level profile</td>
<td>18</td>
</tr>
<tr>
<td>17</td>
<td>Wind rose for Gävle</td>
<td>18</td>
</tr>
<tr>
<td>18</td>
<td>Annual irradiation of Gävle</td>
<td>19</td>
</tr>
<tr>
<td>19</td>
<td>Model for condensation risk prediction</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>General IDA model</td>
<td>22</td>
</tr>
<tr>
<td>21</td>
<td>Ida model for the staircase</td>
<td>22</td>
</tr>
<tr>
<td>22</td>
<td>Picture of the thermometer TECHNOTERM 1500</td>
<td>23</td>
</tr>
<tr>
<td>23</td>
<td>Picture of the hygrometer VELOCICALC Plus TSI</td>
<td>23</td>
</tr>
<tr>
<td>24</td>
<td>Properties of a window</td>
<td>24</td>
</tr>
<tr>
<td>25</td>
<td>U-value</td>
<td>25</td>
</tr>
<tr>
<td>26</td>
<td>Performance data</td>
<td>26</td>
</tr>
<tr>
<td>27</td>
<td>Properties with Bioclean coating</td>
<td>26</td>
</tr>
<tr>
<td>28</td>
<td>Photocatalytic action for Bioclean coating</td>
<td>27</td>
</tr>
<tr>
<td>29</td>
<td>Hydrophilic action for Bioclean coating</td>
<td>27</td>
</tr>
<tr>
<td>30</td>
<td>CAD model</td>
<td>29</td>
</tr>
<tr>
<td>31</td>
<td>Energy balance staircase</td>
<td>29</td>
</tr>
<tr>
<td>32</td>
<td>Plume for a cold surface</td>
<td>31</td>
</tr>
</tbody>
</table>
Figure 34. Description of roof ................................................................. 32
Figure 35. Pictures of the holes .............................................................. 34
Figure 36. Thermal buoyancy in a building with two openings ................. 35
Figure 37. Parameters of a door ............................................................ 36
Figure 38. Air exchange for 3 seconds door opening .................................. 37
Figure 39. Heat losses ........................................................................... 38
Figure 40. Thermal behaviour of glass .................................................... 39
Figure 41. Angle of incidence ............................................................... 40
Figure 42. Sunpath on Winter solstice ...................................................... 40
Figure 43. Representation of the azimuth ................................................ 40
Figure 44. Description of floor .............................................................. 42
Figure 45. Temperature distribution through window ................................ 43
Figure 46. Resistance method .............................................................. 43
Figure 47. Resistance method for moisture ............................................. 45
Figure 48. RH of exterior and interior air ............................................... 54
Figure 49. Outdoor temperature at condensation for the different months analyzed .... 54
Figure 50. Monthly indoor temperatures with IDA .................................. 55
Figure 51. Window surface temperature with IDA .................................. 55
Figure 52. RH indoors with IDA ............................................................ 56
Figure 53. Two pane window configuration .......................................... 57
Figure 54. Two pane window with low $\varepsilon$ coating ............................. 58
Figure 55. Standard vs Drained glazing units ........................................ 59
Figure 56. Secondary glazing ............................................................... 64
Figure 57. Secondary glazing measurements ......................................... 64
Figure 58. Principle of electrically heated window ................................... 65
Figure 59. Heat transfer without and with energy film ............................ 68
Figure 60. Properties of the Energy film ............................................... 68
Figure 61. Moniflex film .......................................................................... 69
Figure 62. Clear glass vs glass with low-emittance coatings .................... 70
Figure 63. Spectral wavelengths .......................................................... 70
Figure 64. Principle for summer and winter of low $\varepsilon$ films .................. 71
Figure 65. Selection of radiator ............................................................ 73
Figure 66. Working principle of ACU .................................................... 75
Figure 67. Principle of dehumification .................................................. 75
Figure 68. Arrangement of an enthalpy wheel ................................................................. 76
Figure 69. Condensate trap ............................................................................................. 77
Figure 70. Interior, Exterior, Surface and Dew Point temperatures ............................... 79
Figure 71. Moisture contributions .................................................................................. 80
Figure 72. Comparison between 1 and 2 pane window ............................................... 80
Figure 73. Single pane vs electrically heated window .................................................... 81
LIST OF TABLES

Table 1. Parameters of Gävle ................................................................. 4
Table 2. Window specifications ............................................................ 5
Table 3. Window vs Wall surfaces ...................................................... 5
Table 4. Temperature ranges as switch limits ................................. 16
Table 5. Temperature analysis, Gävle ................................................ 17
Table 6. Inside temperatures and RH measured .............................. 24
Table 7. Outside temperature and RH measured .............................. 24
Table 8. Energy balance ..................................................................... 30
Table 9. Monthly average irradiation ............................................... 41
Table 10. Desirable humidity levels ................................................ 46
Table 11. Humidity levels depending on temperature ..................... 46
Table 12. Humidity content coming through apartments’ doors .... 47
Table 13. Humidity content coming through the main door .......... 48
Table 14. Indoor temperatures .......................................................... 50
Table 15. Distribution of temperatures ........................................... 51
Table 16. Surface temperatures and humidity at saturation .......... 52
Table 17. Interior humidity content .................................................. 53
Table 18. Dew point temperatures .................................................. 53
Table 19. Inside temperature for 2 pane window ......................... 59
Table 20. Results with IDA software for 2 pane window ................. 60
Table 21. Indoor temperature for a 3 pane window ....................... 60
Table 22. Comparison of outward heat flow ................................... 61
Table 23. Outdoor temperature at condensation for single, double and triple pane windows for October ................................................. 61
Table 24. Savings by adding panes .................................................. 62
Table 25. Electrical specifications of the film ................................. 66
Table 26. Optical specifications of the film ..................................... 66
Table 27. Indoor temperatures with heated glass ......................... 66
Table 28. Humidity content at saturation ........................................ 67
Table 29. Energy price of running the panels ................................. 67
Table 30. Comparison between window films ............................... 71
Table 31. Radiator power for different cases .................................. 73
NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
<td>[m²]</td>
</tr>
<tr>
<td>U</td>
<td>U-value</td>
<td>[W/m²K]</td>
</tr>
<tr>
<td>V</td>
<td>Wind velocity</td>
<td>[m/s]</td>
</tr>
<tr>
<td>G</td>
<td>Solar Heat Gain Coefficient</td>
<td>[%]</td>
</tr>
<tr>
<td>Q</td>
<td>Heat flow</td>
<td>[W]</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>$\dot{q}$</td>
<td>Air flow</td>
<td>[m³/s]</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Moisture content</td>
<td>[g/kg]</td>
</tr>
<tr>
<td>Cd</td>
<td>Discharge coefficient</td>
<td>-</td>
</tr>
<tr>
<td>I</td>
<td>Irradiance</td>
<td>[W/m²]</td>
</tr>
<tr>
<td>Cp</td>
<td>Specific Heat</td>
<td>[J/kg K]</td>
</tr>
<tr>
<td>RH</td>
<td>Relative Humidity</td>
<td>[%]</td>
</tr>
</tbody>
</table>
**Greek symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ</td>
<td>Air density</td>
<td>[kg/m³]</td>
</tr>
<tr>
<td>ε</td>
<td>Emissivity</td>
<td>-</td>
</tr>
<tr>
<td>θ</td>
<td>Angle of incidence</td>
<td>[°]</td>
</tr>
<tr>
<td>δ</td>
<td>Permeability</td>
<td>[m/s]</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1 Background

The building facade in general can be understood as a skin, similar to the skin of the human body. It is the building part that encloses the building, and must be able to efficiently protect from all external influences such as temperature, wind, rain, and sound. However, transparent areas in the facade also serve as the point of contact between the exterior and the interior. Furthermore, the facade must be able to transfer air and daylight into the inner space to ensure a high comfort level. Thus, the facade serves the function of an interface between the interior and the exterior.

During the past decades, large windows and glazed facades have become an important part of modern architecture and they are designed frequently in both public and residential buildings. Glazed buildings are considered to be airy, light and transparent with more access to daylight. However, there is insufficient knowledge concerning the function, energy use and visual environment of glazed buildings for Scandinavian conditions, like Sweden. [1]

Nevertheless, besides the positive effect of such a design on building occupants, large windows may cause thermal discomfort as cold inner window surface may generate draught in the occupied zone. Thermal comfort is usually assessed by measuring air temperature, relative humidity, air velocity and heat transfer due to radiation.

Recently, higher levels of insulation, lower infiltration rates and larger areas of glazed aperture have been demanded of building. In view to this increasing demand, the conventional window has become the weakest thermal fabric in a building.

Due to cold climates and inappropriate thermal conditions inside the building, condensation may appear on the inner surface of the glazed area. Condensation might be described as the modern disease of buildings [2]. In buildings, condensation on window glazing may obstruct the view and, if it becomes so excessive and no means for drainage is provided within the window frame, condensed water will run off causing damage to woodwork, furniture and decorations.

Therefore a project was initiated in order to gain knowledge of the possibilities and limitations of glazed buildings regarding energy use and indoor climate issues.
1.2 Problem description

The problem to be analyzed is the condensation that appears on the inner surface of a large vertical window located in the staircase of Fullriggaren building in Gävle, Sweden.

The city of Gävle is characterized with the following parameters.

<table>
<thead>
<tr>
<th>Latitude (º)</th>
<th>Longitude (º)</th>
<th>Elevation (m)</th>
<th>Time zone (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.7 North</td>
<td>17.1 West</td>
<td>21.2</td>
<td>1 E</td>
</tr>
</tbody>
</table>

Table 1. Parameters of Gävle

Fullriggaren is a 2011 year building that is 42 meters tall. It has 12 different floors. It can be seen in Figure 1.

![Figure 1. Fullriggaren building](image)

The window to be studied is the one marked in red in the Figure.
From a constructive point of view, the characteristics of the window can be seen in the following table.

<table>
<thead>
<tr>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Area (m²)</th>
<th>Orientation</th>
<th>Glazing design</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>34.02</td>
<td>115.67</td>
<td>North</td>
<td>Active glass</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 2. Window specifications

The window surface can be compared to the whole wall in Table.

<table>
<thead>
<tr>
<th>Total wall area (m²)</th>
<th>Total glass area (m²)</th>
<th>Window to wall ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>256.15</td>
<td>115.67</td>
<td>45.15</td>
</tr>
</tbody>
</table>

Table 3. Window vs Wall surfaces

These dimensions can be seen in the following CAD image of Figure

Figure 2. Window to be analyzed

Figure 3. CAD dimensions
The condensation to be studied is due to the cold climates that the city of Gävle suffers plus the consequence of an errant design when the facade was built. This window counts with only one pane, which makes the temperature of the inner surface be practically the temperature outdoors. This is not enough to conserve the required environmental conditions inside the staircase. Indeed windows facing between North-East and North-West are more susceptible to prolonged condensation and this is why the most efficient glazing type should be installed on the North.

When the humid air in the staircase touches the cold surface, condensation takes place on this surface. The water drops condensed on the window surface will drop causing damage to the painting, making corrosion in the metallic parts and allowing mould growth.

This project will be developed in the best means to support a design of a building facade in combination with building services functions in order to reach a solution that is both adapted to the local climate and offers energy-reduced operation. It will allow obtaining proper thermal conditions indoors which will avoid the problems that the condensation was causing. This is the main reason why an energetic study of the staircase is necessary. In this way, the thesis will contribute to the study of different possibilities and limitations of buildings with large glazed surfaces from energy use point of view for countries with similar climate.

The project will be developed in collaboration with Sweco Company. This enterprise is subcontracted by Gavlegardarna, which was the one in charge of the construction and calculations relative to the building.

1.3 Objectives

The following objectives derive from the preceding problem definitions and form the motivation for this Thesis.

- Create an understanding of the interrelation between facade, building services (mechanical installations), comfort and climate zone
- Establish an energy balance by analyzing the heat and moisture transfer in the building envelope
- Comparison with two pane window energy balance
- Find possible solutions for the current structure


2. THEORY

2.1 Main concepts

The most common surface moisture related problems, regardless of the climate, are mold, mildew and condensation. The single most important factor influencing these problems is relative humidity near surfaces.

Air is capable of holding moisture in the vapor phase. The amount of moisture contained in air is referred to as **absolute humidity**. More precisely, the absolute humidity is the ratio of the mass of water vapor to the mass of dry air. The amount of moisture that the air can hold (absolute humidity) is dependent on the temperature of the air. The warmer the air is, the greater the amount of moisture it can hold; the cooler the air is, the less moisture it can hold.

Air is said to be saturated when it contains the maximum amount of moisture possible at a specific temperature, or 100%. This is referred to as **saturated air**.

Since air absorbs water vapor depending on the temperature, it is needed to differentiate between absolute and relative humidity. **Relative humidity** is defined as the amount of moisture contained in a unit of air relative to the maximum amount of moisture the unit of air can retain at a specific temperature.

Room air humidity plays an equally important role as the thermal aspects. The human body senses the climate as muggy at water vapor contents of approximately 14g. A comfortable level of relative humidity lies between 30 and 65% (DIN, 1994-01).

‘**Relative humidity increases as temperature decreases**’.

Cold air is not capable of holding very much moisture, so cold air is dry and has a low vapor pressure. Although cold air cannot contain very much moisture, some moisture in the air is always present. However, this small amount is often very close to the maximum amount of moisture the air can hold at that temperature, so the air is at a very high relative humidity. Since the capacity of the air to hold moisture is reduced as temperature is decreased, only a very small addition of moisture is required to bring it to saturation [3] [4].
2.2 Psychrometric chart

Graphs can be used to facilitate calculating fluctuations of the condition of the air.

A relative humidity reading taken inside an enclosure will not give an accurate indication of the actual amount of moisture present unless a temperature reading is taken at the same time. The relationship between temperature, relative humidity, and vapor pressure is presented graphically on psychrometric chart. A psychrometric chart is mainly used to describe climate data and human thermal comfort conditions. The main assumption in psychrometrics is that humid air can be treated as a mix of two gases, dry air and water vapor (steam) [5].

The Mollier chart depicts temperature on the vertical and water content on the horizontal axis whereas the opposite is true for the Carrier chart (Siemens, 2001). In principle both models are set up the same way, but the axial direction is different.

A representation of it can be seen in the Figure below.

![Psychrometric Chart](image)

**Figure 4. Properties of moist air on a psychrometric chart.**

Now, the parameters that take part in this chart will be described.

- **Dry bulb temperature**: This is one of the most important variables of thermal comfort. It is the most common measure of temperature as measured by a thermometer with a dry bulb.

  On the graph, the vertical lines represent dry bulb temperature. As higher temperatures are considered, it means that there is more sensible heat.
- **Absolute humidity**: It is the amount of moisture in the air as measured in kg of water per kg of dry air. On the graph, the absolute humidity is represented by horizontal lines. Points higher up on the chart have more moisture, whereas points in the lower part have less.

- **Saturation line**: The saturation line represents the maximum amount of humidity that the air can hold. Here, it can be observed what was mentioned before: ‘air can hold more moisture as temperature increases’.

- **Relative humidity**: This concept, as explained above, is related to the previous concept of saturation line. Relative humidity is the percentage of humidity in the air relative to the saturation line that can be held as maximum.
- **Wet-bulb temperature**: It is the temperature as measured by a thermometer whose bulb is surrounded by a damp wick. It is used to show adiabatic changes on the Psychrometric chart, this is, changes that do not result in a change of the total heat content of the air.

On the graph, wet bulb temperatures run diagonally up and to the left. It is always lower than the corresponding dry bulb temperature because evaporation makes it cooler.

- **Dew-point temperature**: It is the temperature at which the air becomes completely saturated and the water starts to precipitate out of the air.
- **Precipitation**: It is the amount of water that is taken out of the air by a surface that is below the current dew point temperature

![Figure 11. Representation of precipitation on the psychrometric chart](image)

### 2.3 Condensation: causes and consequences

Condensation within a building can form as visible surface condensation or can form on surfaces within the building fabric, known as interstitial condensation. In cold weather, interstitial condensation is caused when water vapor inside a building is able to move outward via diffusion through permeable building fabrics or air movement and reach a surface within the building cavity that is below the dew point. On the other hand, superficial condensation is a natural phenomenon which occurs when warm moist air comes into contact with a cold surface, which cools the air below its saturation point, causing its water vapor to condense [6].

This can happen on any cold surface within the building such as plastered wall or a pane of glass. Condensation on glazings may obstruct the view through window and, if it becomes so excessive and no means for drainage is provided within the window frame, condensed water will run off causing damage to window frame, furniture and paintwork.

Single-glazed windows are considered the weakest thermal elements in building. In winter time, the temperature of the glass pane approaches the outside ambient temperature. The airborne moisture in the vapor phase of the indoor air which is in contact with the glass surface is removed from the air and deposited on the interior surface of the window discards forming condensation. The colder the window, the greater the amount of moisture removed from the air. The window is acting as a dehumidifier for the room.
Windows facing between north-east and north-west are more susceptible to prolonged condensation, whereas southerly facing windows that take advantage of solar heat gain may not be so badly affected.

The temperature of the surface depends on the following factors [6]:

a) the type(s), amount, time and rate of heating of the building
b) the ventilation rate
c) the thermal properties and surface finish of the building fabric
d) the external temperature

The vapor pressure of the air is determined by:

a) the water vapor production within the building
b) the ventilation rate
c) the moisture content of the “replacement” outdoor air
d) the ability of the building fabric and contents to absorb or desorb water vapor (sponge effect). This will reduce or increase the vapor pressure depending on whether the building is cooling or heating.

Causes [7]:

- The effect of infiltrated external air: In cold weather, the temperature of the external air is usually so cold that its moisture content is very low even if its relative humidity is 100%. Thus, if very cold air infiltrates inside the building, the moisture increase within the building will be low.

- The effect of internal air: The most susceptible parts of a dwelling to condensation are those areas which are not heated or inadequately heated. Heating of a building is important in many respects. Firstly, internal warm air can carry more water vapor than cold air. Therefore water vapor which cold air cannot carry will be suspended in the warm air. Secondly, if heating of a building is supplied in consistent levels, it will keep the internal surfaces warm and above dew point. These 2 aspects will be discussed in the ‘Solutions’ part.

- The effect of ventilation: It is theoretically possible to avoid all condensation by adequate ventilation. The paradox that faces building professionals nowadays is that, on the one hand, the greater the ventilation, the greater the heat necessary to replace that which is lost by ventilation, and consequently the greater the cost, especially with the
presently high prices of fuel. On the other hand, the less the ventilation and the heat input to the building, the more likely the condensation occurrence.

**Consequences:**

The failure to consider condensation within the built environment can have serious consequences. Some of them include:

- visible and hidden fungus and mould growth
- sick building syndrome leading to serious health problems
- timber decay
- phantom leaks
- saturation of insulation and loss of insulation effectiveness
- corrosion
- loss of structural integrity
- health and safety risk arising from slippery floors

**Figure 12. Images of problems caused**

In what regards reduced effectiveness of insulation materials, where condensate accumulates in insulation materials, even at levels as low as 1% by volume, it can significantly reduce the thermal resistance of the insulation, as illustrated by the Figure below. This is because the air gaps in porous insulation are replaced by water, which is a better conductor of heat [3].
Figure 13. Effect of moisture on the measured thermal conductivity

The WHO\textsuperscript{1} introduced the name of Sick Building Syndrome (SBS) symptoms, which is a term used to describe a range of symptoms, such as respiratory difficulties, itchy eyes, skin rashes, and nasal allergy, which may be triggered when the sufferer spends time in a particular building. One of the key contributory factors behind cases of sick building syndrome is moisture and related mould growth.

Mould requires oxygen, food, spores and water to germinate and grow. However, water availability is the primary factor controlling mould growth in buildings.

The best information currently available is that a surface surrounded and at equilibrium with a relative humidity greater than 80\% for a prolonged period (a month or longer) is adequate to cause germination and mould to grow on most common building surface materials, such as emulsion coated plaster or wallpaper [8].

\textsuperscript{1} The World Health Organization
3. CLIMATIC CONDITIONS

Understanding the local climate that the building is exposed to, is important to ensure that appropriate principles are applied and that suitable climate data is used in any condensation risk assessment that is undertaken.

At the beginning of the project, the weather data record is to be analyzed to provide easy-to-understand information about the prevailing conditions at a particular location.

When designing a building, the initial study should provide solutions for the following aspects of the early conceptual phase:

- Can natural ventilation be achieved?
- Is heating/cooling necessary?
- What glazing ratio is necessary to obtain sufficient daylight?
- Requirements in terms of geographic direction?
- Is dehumidification or humidification necessary, and how much building services are needed?

To answer these questions, it is needed to have thorough knowledge of the local climate. The analysis must be based on weather data records derived from hourly measurements over one year (8760 hours).

For the case of city being analyzed, the data was obtained through simulation thanks to METEONORM program. Meteonorm software is a meteorological database for engineering applications in any part of the world. Thanks to his informatics program, the thermal conditions for the city of Gävle have been obtained on an hourly base for each month of the year. The information provided which will serve as the basis of the study is from year 2011, which was slightly warmer, and this could carry along some variations for the other years.

Meteonorm program provided the following measurement data amongst others:

- Position incl. city, country, state, elevation, time zone, etc.
- Air temperature
- Relative humidity
- Wind speeds/frequency
- Wind direction
- Intensity of global radiation
The climatic conditions of the city of Gävle are the origin of the problem and they will be the factor that influences the results the most.

3.1 Temperature

The weather data record is based on one measurement reading per hour. The temperature across one year can easily be graphed out in a diagram.

![Temperature Graph](image)

**Figure 14. Annual Temperature profile of Gävle**

Temperature can be subdivided into different ranges. The following temperature ranges lend themselves to classification because they are used in the habitual language use and have been selected as switch limits:

<table>
<thead>
<tr>
<th>Temperature ranges</th>
<th>Switch limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very cold</td>
<td>-100°C &gt; Temp &lt; -10°C</td>
</tr>
<tr>
<td>Cold</td>
<td>-10°C &gt; Temp &lt; 10°C</td>
</tr>
<tr>
<td>Cool</td>
<td>10°C &gt; Temp &lt; 15°C</td>
</tr>
<tr>
<td>Moderate</td>
<td>15°C &gt; Temp &lt; 28°C</td>
</tr>
<tr>
<td>Hot</td>
<td>28°C &gt; Temp &lt; 35°C</td>
</tr>
<tr>
<td>Very hot</td>
<td>35°C &gt; Temp &lt; 100°C</td>
</tr>
</tbody>
</table>

**Table 4. Temperature ranges as switch limits**

The weather data records are analyzed according to these temperature ranges and the 8760 hours of one year are subdivided accordingly.
Temperature | Switch limits | Time in range | % of Year in Range
--- | --- | --- | ---
Very cold | -100°C > Temp < -10°C | 235 hours | 2.68
Cold | -10°C > Temp < 10°C | 5583 hours | 63.73
Cool | 10°C > Temp < 15°C | 1454 hours | 16.60
Moderate | 15°C > Temp < 28°C | 1485 hours | 16.95
Hot | 28°C > Temp < 35°C | 0 hours | 0
Very hot | 35°C > Temp < 100°C | 0 hours | 0

Table 5. Temperature analysis, Gävle

3.2 Humidity

The humidity level is an important aspect of the comfort level in a room; the glazed part of the facade, however, does not have any influence on this parameter. But the humidity content gives an indication of the possibility to employ natural ventilation.

The climate is analyzed according to the measurement values; ranges in excess of 12g/kg absolute humidity are considered “humid”. If the climate is considered too humid too often, suitable measures must be taken to dehumidify. In this case, humidity might have an influence on the facade.

![Relative Humidity Chart](image)

The mean values of humidity for each month of the year have been calculated with the help of the psychrometric chart. The results can be seen in the following Figure.
As it can be observed, the levels stay always below the critique value set (12 g/kg), so there should be no problems related to the external air.

### 3.3 Wind

Wind speed is one factor that can be analyzed from overall wind data. There is no direct requirement that can be derived for the facade. Facades must be wind tight and able to resist prevailing wind loads. Hereby, the building geometry plays an important role.

Average wind speed (m/s) = 2.48
3.4 Radiation

Solar energy striking the earth occurs in the form of direct radiation as well as diffuse radiation. Global solar radiation measured in kWh/m²/y describes the amount of radiation received per horizontal square meter surface per year. Due to the orientation of the earth to the sun, global solar radiation is strongest near the equator and lessens toward the poles.

The window, as a transparent windshield, allows short wavelengths of visible light be transmitted through it. Nevertheless, the longer wavelengths of the infrared re-radiation from the heated objects are unable to pass through it. This is the principle of the greenhouse effect.

The amount of global horizontal radiation in throughout a year for Gävle can be plotted on a bar chart like the following Figure.

![Irradiation (W/m²)](image)

Figure 18. Annual irradiation of Gävle
4. METHOD

4.1 Description

Modern buildings have high energy savings potential and potential for indoor climate improvements. The current trend to reduce the heat losses by building components has resulted in many modifications of the design work of the windows in order to improve their thermal performance as they have direct effects on the indoor climate and the thermal comfort.

‘Calculation method’ contains a method for calculating the internal surface temperature of the window where condensation is likely, given the internal temperature and relative humidity. In order to predict condensation, both heat transfer and moisture transfer over the building envelope will be studied taking into consideration the constructive characteristics of the building considered.

The parameters considered to determine the risk of surface condensation and consequent mould growth are summarized as [9]:

1. External climate: temperature and relative humidity
2. The thermal resistance of the building envelope taking into account geometry and internal surface resistance. This is referred to as the “thermal quality” of each building envelope element.
3. Internal temperature and relative humidity for each month of the year paying particular attention to moisture sources

The schema below describes the general procedure for the process [9].

![Figure 19. Model for condensation risk prediction](image-url)
If the case of Fullriggaren building is specifically studied, the number of occupants of the staircase could be stated as none. Moreover, as there is no heating system, the fuel expenditure will also be zero.

The internal surface temperature at any point will depend on the nature of the structure, especially the presence of any thermal bridges causing multidimensional heat flow, and most importantly, the value of the internal and external surface resistances (*see Appendix 1*). Once the temperature inside the stairwell has been established, the moisture transfer will be analyzed to state the relative humidity at which it should be kept to avoid condensation risks. This will be done for the most adverse conditions.

### 4.2 IDA model

The IDA ICE 4.5 (Indoor Climate and Energy) is a dynamic multi-zone simulation application for accurate study of thermal indoor climate of individual zones as well as the energy consumption of entire buildings. It works through a building model with different windows and zones in order to predict the indoor climate and energy use by the building simulated. It will allow calculating different variables as air and surface temperatures, as well as humidity, air and heat flows, comfort values and so on.

The main goal of this study was to determine the environmental conditions in the staircase at which condensation appears and compare them in cases of different window properties.

A room with three external and one internal wall was created and the large window was designed in the North facade of the building. Air supply and exhaust openings for natural ventilation were modeled on the opposite corners and heights of the room. The window is installed throughout the whole wall height with no heating equipment below.

Windows of different constructions and having different heat transmission coefficients were modeled. Three basic models were created with one, two and three pane windows. Apart from that zone, two more zones were necessary to simulate the garage under the staircase and the apartments. For the zone of the apartments, a temperature control was installed setting requirements of temperature to be between 21 and 25ºC. If the temperature is outside this range, heaters or coolers will start running.
In the following Figure, it can be observed the connections that the model built in IDA considers. It can be seen how the radiation goes through the window and also the opening schedule of doors amongst others.

In order to check if the IDA prediction results reflect the nature of the physical phenomenon, a hand-made study for winter months will also be performed basing them on an energy balance. IDA simulations were performed with the same boundary conditions as were used for the energy balance. U-value of the window and frames was selected equal to 5.7 W/m²K. The external temperature was set for the different days of the year according to the data from Meteonorm and the geometries of the model were equated to the ones used in the energy balance.
4.3 Experimental procedure

The temperatures measured here are the air temperatures in both outdoors and indoors. Experimental investigations have been carried out in Fullriggaren building.

Measurement devices

- Thermometer TECHNOTERM 1500: It will allow measuring the temperature of the inside air.

![Figure 22. Picture of the thermometer TECHNOTERM 1500](image)

- Hygrometer VELOCICALC Plus TSI: It will be used to measure the relative humidity in the inside of the staircase in order to determine the characteristics of the inner air.

![Figure 23. Picture of the hygrometer VELOCICALC Plus TSI](image)
Example of collected data (15th April)

Indoors:

<table>
<thead>
<tr>
<th>Floor</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14th</td>
<td>13.3</td>
<td>37.6</td>
</tr>
<tr>
<td>8th</td>
<td>13.1</td>
<td>38.9</td>
</tr>
<tr>
<td>5th</td>
<td>12.3</td>
<td>37.7</td>
</tr>
<tr>
<td>2nd</td>
<td>11.7</td>
<td>37.5</td>
</tr>
</tbody>
</table>

Table 6. Inside temperatures and RH measured

Outdoors:

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Relative Humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.8</td>
<td>31.7</td>
</tr>
</tbody>
</table>

Table 7. Outside temperature and RH measured

Measurements were only made during the month of April, but the results obtained for the data collected for those days showed no risk of condensation as it was expected. Indeed, as it will be calculated after, these temperatures will be above dew point temperature. In order to predict condensation, an energy balance is necessary to calculate the indoor temperature for the rest of the months.

4.4 Glazing type

A well-designed window should have the required properties to retain the vapor indoors while leaving outdoors the rain, noise… It must also be able to let the light in and permit the vision from the inside to the outside. At the same time, it must minimize the heat transfer through it. This can be appreciated in the following Figure.

![Figure 24. Properties of a window](image-url)
All mentioned above will depend on the following parameters:

- **U-value**: Heat transmittance through a surface by conduction, convection and radiation is expressed by its U-value. This is the rate of heat loss per square meter for a temperature difference of 1 degree Kelvin, or Celsius, between the interior and exterior. It is calculated using the surface exchange coefficients $h_e$ and $h_i$ (external and internal resistances). It is possible to calculate a specific U-value by using design values of the surface exchange coefficients, which will take into account environmental variants, such as wind speed. The lower the U-value, the lower the heat loss.

![Figure 25. U-value](image)

- **Solar Heat Gain Coefficient (SHGC, $g$)**: The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted and absorbed and subsequently released inward. The lower a window's solar heat gain coefficient, the less solar heat it transmits. Solar heat gains through windows can either contribute positively or negatively towards a building's energy efficiency. The impact of solar gains will vary with building type and use, climate, season, and even time of day. Unlike window U-values, where lower U-values are almost always better, there is not a universal goal for Solar Heat Gain Coefficients.

- **Visible Transmittance**: The visible transmittance (VT) is an optical property that indicates the amount of visible light transmitted. VT is a whole window rating and includes the impact of the frame area. Since the frame does not transmit any light, the VT may be lower than expected; however, this is done to be consistent with the whole window ratings of U-factor and SHGC. While VT theoretically varies between 0 and 1, most values among double- and triple-pane windows are between 0.30 and 0.70. The higher the VT, the more light is transmitted. A high VT is desirable to maximize daylight.

- **Air Leakage**: Heat loss and gain occur by infiltration through cracks in the window assembly and an air leakage rating (AL). It is expressed as the equivalent cubic meter of
air passing through a square meter of window area. The lower the AL, the less air will pass through cracks in the window assembly.

The window under consideration is a single-pane window of a thickness of 6 mm. Its U-value is 5.7 W/m²K which can be obtained from the data sheet of Saint Gobain Glass (See Appendix 2).

The following Figure represents the parameters that are shown in the data sheet.

![Figure 26. Performance data](image)

The glazed facade at Fullriggaren building is provided with an extra coating for self cleaning (SGG Bioclean). The term self-cleaning means that the process of cleaning the glass is carried out, or at least assisted, by natural elements. A permanent, transparent coating on the outside surface of the glass harnesses the power of both sun and rain to efficiently breakdown and remove dirt and grime such as dried, dirty water marks, dust and insect residues [10].

![Figure 27. Properties with Bioclean coating](image)
The self cleaning process can be seen in the following sequence:

- Step 1: ‘Photocatalytic’ action. Ultra-violet rays present in daylight trigger the decomposition of organic dirt and cause the surface of the glass to turn hydrophilic.

![Figure 28. Photocatalytic action for Bioclean coating](image)

- Step 2: The hydrophilic action: thanks to this special hydrophilic, a water film is formed when rain makes contact with the surface of the glass. The film allows the broken-down dirt particles and mineral dirt to be rinsed clean away.

![Figure 29. Hydrophilic action for Bioclean coating](image)
5. ENERGY ANALYSIS

Windows and energy conservation

The importance of discussing energy in architecture is undeniable since the building industry uses more than 50% of the resources used worldwide and holds accountable for more than 60% of all waste\(^2\). The consequences of these numbers are obvious: more than any other this sector drives the demand as well as the potential for change.

Most of the energy used today originates from fossil fuels (gas, oil and coal). Burning fossil fuels emits pollutants, including carbon dioxide and gases that cause acid rain. As carbon dioxide and other gases build up in the atmosphere, more of the sun's heat is trapped (the greenhouse effect). This could result in the earth becoming hotter (global warming), which may also increase the risk of storms, coastal flooding and drought.

Using energy more efficiently is one of the most cost effective means of reducing emissions of carbon dioxide and also helps to conserve fossil fuels.

About forty million square meters of Swedish windows in residential buildings let out 15 terawatt-hours of heat every year. This is more than a fifth of the energy supplied by Swedish nuclear plants [11].

Therefore, improving the thermal insulation of the window will contribute to energy conservation and environmental betterment by reducing the heat loss from a building shell. This, in turn, reduces the amount of fossil fuels to be burnt and hence the greenhouse gases, such as CO\(_2\) released in to the atmosphere. Insulating roofs and walls is a good idea, but getting the right windows often saves more energy, environment and money. If all uncoated single and double pane windows in the European Union were replaced with low-e double glazing combinations, more than a billion Giga Joules of energy per year could be saved (more than 300 terawatt-hours). More than 80 million tons of CO\(_2\) emissions could be avoided. The total energy use and emissions would be reduced by almost 3 % and more than 14 billion euro per year would be saved, according to the Groupement Europeen des Producteurs de Verre Plat [12].

As mentioned above, the facade or building envelope plays a significant role in the energy consumption of a building. Since it functions as the interface between interior

\(^2\) Hegger et al.,2007
and exterior in addition to enclosing as well presenting the outer appearance of the entire building it provides great potential for innovative solutions and constructions.

5.1 Heat transfer

As it has been impossible to measure the temperature of the air inside for previous months, it could be calculated from the energy balance in the staircase. The different inputs and outputs that take place in the volume of control will be considered. The volume of control to be analyzed is the staircase itself. Its dimensions can be seen in the following Figure.

![Figure 30. CAD model](image)

Volume staircase = 7.385 x 34.685 x 2.327 = 596.06 m$^3$

The different terms to be considered in the heat balance can be seen in the following Figure.

![Figure 31. Energy balance staircase](image)
The energy balance to be studied is the following:

\[ Q_{in} = Q_{out} \]

<table>
<thead>
<tr>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_{radiation}</td>
<td>Q_{roof}</td>
</tr>
<tr>
<td>Q_{floor}</td>
<td>Q_{window}</td>
</tr>
<tr>
<td>Q_{rooms-staircase}</td>
<td>Q_{walls}</td>
</tr>
<tr>
<td>Q_{ventilation}</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Q_{snow}</td>
</tr>
</tbody>
</table>

Table 8. Energy balance

5.1.1 Heat losses

The heat losses to be studied as mentioned above will be losses through the roof, walls, window, losses due to ventilation and losses due to the melting of the snow that inhabitants take with them.

a) Window

The heat losses through the window will be due to both conduction and convection.

\[ A_{window} = 34.02 \times 3.4 = 115.67 \text{ m}^2 \]

Conduction

For the entire window,

\[ Q_{cond} = U_{window} \times A_{window} \times (T_{int} - T_{ext}) = 5.7 \times 115.67 \times (T_{int} - T_{ext}) \]

where,

- \( Q_{cond} \) is the heat flux, W
- \( A_{window} \) is the window surface m²
- \( T_{int} \) is the internal ambient temperature, °C
- \( T_{ext} \) is the external ambient temperature, °C
- \( U_{window} \) is the U-value for the window, W/m²K (See Appendix 2)

Convection (plumes)

Plumes are produced by convection as a result of difference in temperature (buoyancy) between the air in contact with the cold surface of the window. In this way, buoyant
forces are generated which cause this layer of air adjacent to the window to flow in a downward direction. This layer of air adjacent to the wall, to which vertical motion is confined, is called the natural convection boundary layer. The boundary layer begins with zero thickness at the top of the vertical wall and increases in thickness in the downward direction [13].

![Figure 32. Plume for a cold surface](image)

The flow of air for the laminar and turbulent layers for a vertical surface can be calculated according to the following equations [14].

- **Laminar boundary layer**:
  \[ \dot{q} = 2.87 \times 10^{-3} L (T_{surf} - T_{int})^{1/4} H^{3/4} \]

- **Turbulent boundary layer**:
  \[ \dot{q} = 2.75 \times 10^{-3} L (T_{surf} - T_{int})^{2/5} H^{6/5} \]

Where,
\[ \dot{q} \text{ is the volume flow rate (m}^3/\text{s)} \]
\[ L \text{ is the length of surface (m)} \]
\[ H \text{ is the height of surface (m)} \]
\[ T_{surf} \text{ and } T_{int} \text{ are the surface and air temperatures (ºC)} \]

For this case, the flow to be considered is just laminar because of very low flow movements take place there. If it supposed that \( T_{surf} \) is approximately \( T_{ext} \) for one pane windows,

\[ \dot{q} = 2.87 \times 10^{-3} L (T_{ext} - T_{surf})^{1/4} H^{3/4} = 2.87 \times 10^{-3} \times 3.4 \times (T_{int} - T_{ext})^{1/4} 34.02^{3/4} \]

According to this, the heat transfer due to convection can be calculated as follows,

\[ Q_{conv} = \dot{q} \rho C_p (T_{int} - T_{ext}) \]

The basic factors determining air speed close to the window are the height of the cold surface and the temperature difference between the surface and the air in the room. Ge and Fazio (2004) found that large tall windows may generate air speed up to 1 m/s (close to the surface). Heiselberg (1994) presented an empirical equation to calculate
maximum air speed (close to the floor surface). It depends on the distance from the external wall or window (x value) [13]:

\[
\begin{align*}
    v_{\text{submax}} &= 0.055 \times \sqrt{\Delta T \times H} & \text{if } x < 0.4 \text{ m} \\
    v_{\text{submax}} &= \left(0.096 \times \frac{x}{x} + 1.32x\right) \times \sqrt{\Delta T \times H} & \text{if } 0.4 \text{ m} \leq x \leq 2.0 \text{m} \\
    v_{\text{submax}} &= 0.028 \times \sqrt{\Delta T \times H} & \text{if } x > 2.0 \text{ m}
\end{align*}
\]

where,
\(\Delta T\) is the temperature difference between the inner surface of the window or wall and the air temperature in the room and H is the window or wall height.

b) Walls

\[Q_{\text{wall}} = A_{\text{wall}} \times U_{\text{wall}} \times (T_{\text{int}} - T_{\text{ext}}) = 301.91 \times 0.124 \times (T_{\text{int}} - T_{\text{ext}})\]

Where,

\(Q_{\text{wall}}\) is the heat transfer through the external walls
\(A_{\text{wall}}\) is the area of the external walls
\(U_{\text{wall}}\) is the U-value for the external walls (See Appendix 3)
\(T_{\text{int}}\) and \(T_{\text{ext}}\) are the internal and external ambient temperatures, °C

c) Roof

\[Q_{\text{roof}} = U_{\text{roof}} \times A_{\text{roof}} \times (T_{\text{int}} - T_{\text{ext}}) = 0.171 \times 17.18 \times (T_{\text{int}} - T_{\text{ext}})\]

Where,

\(Q_{\text{roof}}\) is the heat transfer through the roof
\(U_{\text{roof}}\) is the U-value of the roof
\(A_{\text{roof}}\) is the roof area
\( T_{\text{int}} \) and \( T_{\text{ext}} \) are the internal and external ambient temperatures, °C

d) Losses due to air gaps

These losses are due to infiltrations (bring in cold air from the exterior) and exfiltrations (take warm air out from the interior) of air due to unavoidable gaps in the construction, this is, air leakages.

The UK standard measures Air Permeability, in \( \text{m}^3/\text{h}/\text{m}^2 \) at 50Pa (the \( q_{50} \) measurement), or in other words the air leakage per square meter of building envelope. The ATTMA\(^3\) TS1 standard defines the building envelope as everything within the air barrier line ‘along the line of the component to be relied upon for air sealing’. This could be anywhere within the building envelope. This is a measure of building envelope air tightness.

If the dimensions of the staircase are introduced in the air leakage calculator, the following results are obtained [15].

- ATTMA Normal Practice Leakage Index flow (5 \( \text{m}^3/\text{hr}/\text{m}^2 \) or 1.39 L/s/m\(^2\) or 0.2734 cfm/ft\(^2\) at 50 Pa) = 0.2521 m\(^3\)/s
- ATTMA Best Practice Leakage Index flow (2.5 \( \text{m}^3/\text{hr}/\text{m}^2 \) or 0.694 L/s/m\(^2\) or 0.1367 cfm/ft\(^2\) at 50 Pa) = 0.1261 m\(^3\)/s

Once the air flow is obtained, the heat loss can be calculated as,

\[ Q_{\text{leakage}} = \dot{q} \rho C_p (T_{\text{int}} - T_{\text{ext}}) = 0.2521 \times 1200 \times (T_{\text{int}} - T_{\text{ext}}) \]

f) Ventilation

The ventilation in the staircase was added after construction in a desperate way to try to avoid the frosting of the windows. Natural ventilation was created by creating 2 holes; one under the stairs, and the second one in the last floor.

---

\(^3\) Air Tightness Testing and Measurement Association
The net energy transfer due to air movement, or the ventilation energy transfer rate in Watts is,

\[ Q_{\text{vent}} = \dot{q} \times \rho \times Cp \times \Delta T \]

Where,
- \( Q_{\text{vent}} \) is the heat removed, W
- \( \Delta T \) is the indoor outdoor temperature difference, K
- \( Cp \) is the coefficient of transmission (over the temperature range from outside to inside, a constant value of \( Cp \) can be used), J/kg K
- \( \rho \) is the density of air, kg/m\(^3\)

For atmospheric air over the normal inside temperature and humidity range, the mean value of the product \( \rho \times Cp \) is approximately equal to 1200 J/m\(^3\)K.

Calculation of rate of ventilation air flow:

\[ \dot{q} = \dot{q}1 + \dot{q}2 + \dot{q}3 \]

- **Air flow due to thermal forces (stack effect):** \( \dot{q}1 \)

The difference in density creates pressure differences that pull air in and out of a building through suitably placed openings in the building envelope. When the indoor air temperature exceeds the outdoor temperature, an over-pressure is built up in the upper part of the building and an under-pressure is formed in the lower part. At a certain height, the indoor and outdoor pressure equals each other, and this level is referred to as the neutral plane. An over-pressure above the neutral plane drives air out through
openings in the building envelope, and an under-pressure under the neutral plane pulls air in through openings in the building envelope.

![Figure 35. Thermal buoyancy in a building with two openings](image)

The total driving pressure for an internal space with two openings is given by [16]:

$$\Delta P_{tot} = \rho_{ext} \cdot g \cdot (h_2 - h_1) \cdot \Delta T/T_{int} = = \rho_{int} \cdot g \cdot (h_2 - h_1) \cdot \Delta T/T_{ext} \quad [\text{Pa}]$$

Thus, the air flow due to the stack effect can be calculated with the following equation.

$$\dot{q} = C_d \times A \times [2g \times (h_{npl} \cdot h) \times (T_{int} - T_{ext}/T_{int})]^{1/2}$$

Where,

- \(q\) = Air flow rate through a large opening (m\(^3\)/s)
- \(C_d\) = Discharge coefficient (0.61 for large openings)
- \(A\) = Opening area (m\(^2\))
- \(g\) = Acceleration due to gravity (9.81 m/s\(^2\))
- \(h_{npl}\) = Height of neutral pressure level above datum (m)
- \(h\) = Height of opening above datum (m)
- \(T_{ext}\) = Temperature of air outside stack (°K)
- \(T_{int}\) = Temperature of air inside stack (°K)

A good approximation for the location of the neutral plane is given by:

$$h_{npl} = (A_1^2 \cdot h_1 + A_2^2 \cdot h_2) / (A_1^2 + A_2^2)$$

Where, \(A_1\) and \(A_2\) is the area of the lower and upper opening respectively [m\(^2\)].

$$\dot{q} = 0.61 \times \frac{\alpha 0.22}{4} \times [2 \times 9.81 \times 17.34 \times (T_{int} - T_{ext}/T_{int})]^{1/2}$$

- **Air flow due to wind**: \(\dot{q}_w\)

The rate of air movement into and out of any space within a building depends on the pressure differences, which in turn are affected by wind direction and speed around the building. Wind driven ventilation occurs as a result of various pressures created on the building envelope by wind. These pressure differences drive air into the building.
through openings in the building envelope’s windward side, and drive air out of the building through openings in the building envelope’s leeward side [16].

\[ \dot{q} = EAV = 0.5 \times 2 \times \pi \times 0.2^2 / 4 \times V \]

\( \dot{q} \) is the air flow in \( \text{m}^3/\text{s} \)

\( A \) is the free area of inlet openings in \( \text{m}^2 \)

\( V \) is the wind velocity in \( \text{m/s} \)

\( E \) is the effectiveness of openings

- 0.5-0.6 perpendicular winds
- 0.25-0.35 diagonal winds

- Air Flow due to opening main door: \( \dot{q}3 \) [17]

The flow through a doorway may be caused by a number of mechanisms:
- Density difference between inside and due to outside temperature differences
- Door swing pumping action
- Passage of personnel through the doorway

Supposition: It will be considered that the door is open the 40% of the time

The total volumetric flow through the opening is given by:

\[ Q = \frac{K \times W}{3} \times \left[ gH^3 \times \left( \frac{\Delta \rho}{\rho} \right) \right]^{1/2} \]

\( K \) is the orifice coefficient = 0.4+0.0075 \( \Delta T \)

\( W \) is the door width

The parameters involved in this equation can be observed in the following Figure.

![Figure 36. Parameters of a door](image)

Considering typical door dimensions of a width of 0.91 m and a height of 2.06 m the generalized results can be seen in the following Figure [18].
If it is considered that the door is held for 3 seconds and it is supposed that the temperature difference is maintained around 7 degrees, the following flow per door is obtained.

\[ q = 22 \text{ ft}^3 = 0.621 \text{ m}^3/\text{door} \]

\[ \dot{q} = 1 \text{ floor} \times 0.621 \text{ m}^3/\text{door} / 3 \text{ sec} = 0.207 \text{ m}^3/\text{s} \]

**g) Heat losses due to snow melting**

It should also be considered the heat losses that are a consequence of the heat needed to melt the snow that inhabitants of the building take with them when they come to the staircase.

This heat can be divided into two as there is going to be a change of state [19].

Sensible heat transferred to the snow: 

\[ Q_s = \rho_{snow} S (C_w T_s - C_s T_{int}) A \]

Latent heat needed to melt the snow: 

\[ Q_l = \rho_{snow} S h_f A \]

Where,

- \( \rho_{snow} \) is the density of the snow (917 kg/m\(^3\))
- \( S \) is the rate of snow fall (m/s)
- \( C_w \) is the specific heat of water (4.18 kJ/kgK)
- \( C_s \) is the specific heat of the snow (2.05 kJ/kgK)
- \( h_f \) is the latent heat (334 kJ/kg)
- \( A \) is the area where the snow is deposited (m\(^2\))

\( S \) has been calculated considering that there is one person that enters in the building each half an hour and deposits 2 mm of snow.
The following pie chart shows the relation between the different heat losses.

![Figure 38. Heat losses](image)

### 5.1.2 Heat gains

a) Heat transfer from rooms to the staircase

As the apartments are warmer than the staircase, there will be a heat flow from the apartments to the staircase through the interior walls.

\[
Q_{\text{rooms-staircase}} = U_{\text{wall rooms}} \times A_{\text{wall rooms}} \times (T_{\text{room}} - T_{\text{int}}) = 0.109 \times 256.15 \times (T_{\text{room}} - T_{\text{int}})
\]

where,

- \(Q_{\text{rooms-staircase}}\) is the heat transfer from the contiguous rooms to the staircase
- \(U_{\text{wall rooms}}\) is the U-value for the wall that separates the rooms from the staircase

(See Appendix 3)

- \(A_{\text{wall rooms}}\) is the surface for the wall that separates the rooms from the staircase
- \(T_{\text{room}}\) is the temperature for the rooms
- \(T_{\text{int}}\) is the temperature in the staircase

It will be supposed that the rooms are kept at a temperature of 21ºC by means of heating or cooling for the different seasons.

b) Heat transfer due to sun radiation

Depending on the glass characteristics, the solar radiation which reaches the window is reflected, transmitted or/and absorbed, and then re-radiated. The part of the radiation that is transmitted through the glass will be considered as heat gains.
Figure 39. Thermal behaviour of glass

The heat transfer due to radiation is calculated through the following equation.

\[ Q_{rad} = g \times A_{window} \times I_{sun} = 0.81 \times 115.67 \times I_{sun} \]

where

- \( Q_{rad} \) is the heat transfer due to radiation
- \( g \) is the total solar energy transmittance through the window (See Appendix2)
- \( I_{sun} \) is the incident solar radiation on a North orientation vertical surface (See Table below)
- \( A_{window} \) is the area through which radiation is transmitted

The data provided by Meteonorm software gives the global horizontal radiation (angle of incidence is zero) per square meter. Nevertheless, the radiation that strikes the window will be the part of that radiation that hits a vertical surface orientated towards North.

The radiation on the \textit{vertical surface} will depend on the angle of incidence by the following equation.

\[ I_{sun} = I_{vert\ surf} = I \times \cos \theta \]

Where,

- \( I_{vert\ surf} \) is the radiation on a vertical surface
- \( I \) is the global horizontal radiation
- \( \theta \) is the angle of incidence
As the Earth rotates around its axis it seems as if the sun crosses the sky from east to west every day. The angle of incidence will vary along the days of the year and at the same time along the hours of the day. It will be considered the day 15 of each month and an average of that day for the angles below 90º. If the angle is above 90º, the window won’t be able to see that radiation.

As mentioned before, North facades are the ones that receive less solar radiation as can be appreciated in the following Figure.

The radiation on the different facades will depend on the surface azimuth, this is, the angle on a horizontal plane between the due-south direction line and the horizontal projection of the sun's rays. For the case of Fullriggaren it is orientated 17.5º towards the NW. Its azimuth would then be 162.5º.
The angle of incidence will be then calculated by an Excel program\(^4\) once the following parameters have been introduced:

- Latitude: 60.7
- Day number: 15 of each month considered
- Surface tilt: 90\(^\circ\) (vertical)
- Surface azimuth: 162.5\(^\circ\) (NW)
- Standard meridian: -15
- Local meridian: -17.3

In the following table, the average sun radiation for each month can be observed.

<table>
<thead>
<tr>
<th></th>
<th>(I_{\text{global horizontal}}) (W/m(^2))</th>
<th>Angle of incidence ((^\circ))</th>
<th>(I_{\text{sun}}) (W/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>88.33</td>
<td>62.89</td>
<td>40.25</td>
</tr>
<tr>
<td>November</td>
<td>32.6</td>
<td>66.02</td>
<td>13.25</td>
</tr>
<tr>
<td>December</td>
<td>20.17</td>
<td>72.1</td>
<td>6.20</td>
</tr>
<tr>
<td>January</td>
<td>40.66</td>
<td>68.94</td>
<td>14.61</td>
</tr>
<tr>
<td>February</td>
<td>81.33</td>
<td>66.06</td>
<td>33.00</td>
</tr>
</tbody>
</table>

Table 9. Monthly average irradiation

c) Heat transfer due to opening the doors that connect to the apartments
   
   Supposition: 2 doors open simultaneously

\[ Q_{\text{doors}} = \dot{q} \rho C_p (T_{\text{part}} - T_{\text{tint}}) \]

\[ \dot{q} = 2 \times 0.621 \text{ m3/door /3 secs} = 0.414 \text{ m}^3/\text{s} \]

\[ Q_{\text{doors}} = 0.414 \times 1200 \text{ (Tpart-Ttint)} \]

d) Floor

As the temperature of the garage is higher than the one of the staircase, the heat will flow from the garage to the staircase, which means a heat gain for the staircase.

\(^4\) Björn Karlsson, SolarAngles_MdH_130415.xls
Figure 43. Description of floor

\[ Q_{\text{floor}} = U_{\text{floor}} \times A_{\text{floor}} \times (T_{\text{garage}} - T_{\text{int}}) = 0.165 \times 17.18 \times (T_{\text{garage}} - T_{\text{int}}) \]

Where,

- \( Q_{\text{floor}} \) is the heat transferred through the door
- \( U_{\text{floor}} \) is the U-value for the floor construction
- \( A_{\text{floor}} \) is the floor area
- \( T_{\text{int}} \) is the temperature of the staircase
- \( T_{\text{garage}} \) is the temperature of the garage

In order to obtain an approximate indoor temperature, it will be considered that the garage will be maintained at 13 °C for the months being considered.

5.2 Moisture Transfer

Moisture may enter a building envelope by various paths, including built-in moisture water leaks, wind-driven rain and foundation leaks. The water vapor in air tries to be equal. Since the air in the apartments is warmer and contains more water vapor, it tries to have an equal amount of water vapor as the cooler air in the staircase. This equalizing is vapor pressure. It will move through the opening of doors and porous materials such as cement, wood, plaster, brick and other types of masonry until it reaches a water-tight barrier such as the paint or siding on the exterior wall. It will collect under the watertight barrier and cause blisters in the paint or siding.

The four moisture transport mechanisms predominant in building science are:

1. Liquid flow due to gravity and/or an air pressure difference
2. Moisture transport due to capillary suction
3. Air movement
4. Vapor diffusion

All moisture movements, and therefore any moisture related problem is a result of one or a combination of these mechanisms.

The analysis of the moisture transfer will determine the humidity present in the staircase for the different cases being considered, and thus, it will determine when condensation on the inner surface of the window appears.

The condition for condensation to appear is the following [20]:

\[ v \text{ indoors} \geq v_{\text{sat}}(T_{\text{surf}}) \]

1) \( v_{\text{sat}}(T_{\text{surf}}) \)

In order to calculate the humidity at which saturation will occur, it is needed to calculate first the temperature on the surface of the window.

![Figure 44. Temperature distribution through window](image)

Using the method of resistances, the construction can be represented as follows:

![Figure 45. Resistance method](image)

By this method, the surface temperature \((T_{\text{surf}})\) can be calculated from the following equations:

\[ P \ (\text{W/m}^2) = U \times (T_{\text{int}} - T_{\text{ext}}) = (T_{\text{int}} - T_{\text{ext}}) / R_{\text{tot}} \]
(Tint − Text) \( \frac{R_{tot}}{R_{int}} = \frac{(Tint − Tsurf)}{R_{ext}} = \frac{(Tsurf − Text)}{R_{ext}} \)

\[ \frac{R_{ext}}{R_{tot}} = \frac{(Tsurf−Text)}{(Tint−Text)} \cdot \frac{R_{int}}{R_{tot}} = \frac{(Tint−Tsurf)}{(Tint−Text)} \]

(Tsurf − Text) = \( \frac{R_{ext}}{R_{tot}} \times (T_{int} − T_{text}) = R_{ext} \times P \)

(Tint-Tsurf) = \( \frac{R_{int}}{R_{tot}} \times (T_{int} − T_{ext}) = R_{int} \times P \)

The same cases that were considered in the heat balance will be studied to obtain the temperature on the surface. These temperatures are displayed in ‘Results’ chapter.

Once the surface temperature for the different cases is determined, it can be known the humidity at which the air will saturate for an established temperature, \( vsat (T_{surf}) \). It can be calculated from the following equation [20].

\[ vsat (T_{surf}) = \frac{a \left(b + \frac{T_{surf}}{100}\right)^n}{461.4 (273.15 + T_{surf})} \left(\frac{kg}{m^3}\right) \]

-20°C < \( T_{surf} < 0°C \)  \( n=12.3; a=4.689; b=1.486 \)

0°C < \( T_{surf} < 30°C \)  \( n=8.02; a=288.68; b=1.092 \)

By substituting these parameters in the equation, the \( vsat (T_{surf}) \) is determined for the different cases considered. In order to obtain g/kg, the values will be divided by the air density. The results will be shown in the following chapter.

2) \( v \) indoors

The humidity inside the staircase will be due to the moisture transfer from outside through the walls, moisture coming with ventilation and the internal moisture generation.

\[ v_{in} = v_{out} + \Delta v \]

Where,

\( v_{out} \) is the humidity level outdoors

\( \Delta v \) is the humidity transfer and generation inside the staircase
Humidity through the walls and natural ventilation

This moisture transfer will be calculated through the resistance method [20].

\[ v_{in} = \frac{k_{out} x v_{out} + k_{ap} x v_{apart} + k_{gar} x v_{garage}}{k_{out} + k_{ap} + k_{gar}} \]

\[ k = \sum \frac{A}{d/\delta} \]

According to the wall constructions and the ventilation,

\[ k_{gar} = \left( \frac{0.020}{2\times10^{-6}} + \frac{0.075}{20\times10^{-6}} + \frac{0.075}{1.25\times10^{-6}} + \frac{0.15}{10\times10^{-6}} \right)^{-1} * 17.185 = 1.94 \times 10^{-4} \]

\[ k_{out} = k_{vent} + k_{wall(\text{ext})} = 0.517 + 40500^{-1} * 301.91 = 0.524 \]

\[ k_{ap} = k_{wall} = 38174.37^{-1} * 256.15 = 6.71 \times 10^{-3} \]

The moisture level will depend on the specific case being considered

- \( v_{out} \) will be provided from Meteonorm data file.
- \( v_{apart} \)

The human body is comfortable when relative humidity ranges between 20 and 60 percent. In the apartments, an average relative humidity of 35 to 40 percent is appropriate when the outside temperature is 20°C or above. Nevertheless, if outside temperature drops, condensation may appear if relative humidity is not controlled [21].

The following table shows recommended indoor humidity levels in relation to outdoor temperatures.
Table 10. Desirable humidity levels

- \( v_{garage} \) will differ for the different cases

The following table shows the different moisture content for outdoors, the apartments and the garage depending on the case considered.

<table>
<thead>
<tr>
<th></th>
<th>( T_{ext} )</th>
<th>( v_{out} )</th>
<th>( v_{apart} )</th>
<th>( v_{garage} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>-8.90</td>
<td>1.739</td>
<td>3.322</td>
<td>9.20</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.408</td>
<td>4.022</td>
<td>5.131</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2.13</td>
<td>3.776</td>
<td>4.350</td>
<td>7.98</td>
</tr>
<tr>
<td></td>
<td>-6.50</td>
<td>1.772</td>
<td>3.854</td>
<td>7.586</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>3.569</td>
<td>4.349</td>
<td>5.696</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
<td>2.877</td>
<td>4.019</td>
<td>7.96</td>
</tr>
<tr>
<td></td>
<td>-15.60</td>
<td>0.8903</td>
<td>2.866</td>
<td>8.63</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>3.810</td>
<td>4.341</td>
<td>6.167</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
<td>2.516</td>
<td>3.937</td>
<td>7.71</td>
</tr>
<tr>
<td></td>
<td>-19.7</td>
<td>0.6575</td>
<td>2.619</td>
<td>9.39</td>
</tr>
<tr>
<td></td>
<td>-2.6</td>
<td>1.769</td>
<td>3.935</td>
<td>5.413</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
<td>2.436</td>
<td>3.998</td>
<td>7.71</td>
</tr>
<tr>
<td></td>
<td>-17.8</td>
<td>0.7877</td>
<td>2.701</td>
<td>9.39</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>1.829</td>
<td>3.967</td>
<td>5.319</td>
</tr>
</tbody>
</table>

Table 11. Humidity levels depending on temperature

Humidity generation

- Snow

The snow that inhabitants of the apartments take with them when they enter in the building will be the main source of internal moisture generation.

In order to do the calculations, it will be considered the generation during the whole day, being the most critical moment the night.

As considered for the heat transfer, the snowfall rate (S) is \( 1.11 \times 10^{-6} \) m/s.

The hypothesis followed will be that each person stays during 5 seconds leaving snow.
It will be considered an average of 2 people/apartment and 4 apartments/floor and 11 floors, a snowfall of is $9.768 \times 10^{-4}$ m/day obtained.
Taking into account that $9.768 \times 10^{-4}$ m/day is equivalent to 0.04884 mm of water; this is 13.187 gr of water.
Thus,

$$v_{\text{snow}} = \frac{13.187 \text{ g Water}}{715.272 \text{ kg Air}} = 0.0184 \text{ g/kg}$$

- Doors that connect with the apartments
For this case, as with the snow, it will be considered the humidity generation during a whole day.

$$q = 0.207 \frac{m^3}{s}, \text{ door} \ast 3\text{ secs open} \ast 10 \text{ doors} \ast 16 \text{ times opens in a day}$$

$$= 99.36 \text{ m}^3 \text{ air}$$

$99.36 \text{ m}^3 \text{ air} \times 1.2 \text{ kg/m}^3 \times v \text{ apart} = \text{ gr water}$

$\text{Vol staircase} = 596.06 \text{ m}^3 \times 1.2 = 715.27 \text{ kg air}$

$$\Delta v = \text{ gr water}/715.272 \text{ kg air}$$

<table>
<thead>
<tr>
<th></th>
<th>$T_{\text{ext}}$</th>
<th>$v \text{ apart}$</th>
<th>$v \text{ doors}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>5.16</td>
<td>4.333</td>
<td>0.722</td>
</tr>
<tr>
<td></td>
<td>-8.90</td>
<td>3.322</td>
<td>0.554</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.022</td>
<td>0.670</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2.13</td>
<td>4.350</td>
<td>0.725</td>
</tr>
<tr>
<td></td>
<td>-6.50</td>
<td>3.854</td>
<td>0.642</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>4.349</td>
<td>0.725</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
<td>4.019</td>
<td>0.670</td>
</tr>
<tr>
<td></td>
<td>-15.60</td>
<td>2.866</td>
<td>0.478</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>4.341</td>
<td>0.724</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
<td>3.937</td>
<td>0.656</td>
</tr>
<tr>
<td></td>
<td>-19.7</td>
<td>2.619</td>
<td>0.434</td>
</tr>
<tr>
<td></td>
<td>-2.6</td>
<td>3.935</td>
<td>0.656</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
<td>3.998</td>
<td>0.666</td>
</tr>
<tr>
<td></td>
<td>-17.8</td>
<td>2.701</td>
<td>0.450</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>3.967</td>
<td>0.661</td>
</tr>
</tbody>
</table>

**Table 12. Humidity content coming through apartments’ doors**
- Main door

Following the same procedure, the humidity that is introduced by opening the main door during the whole day is obtained.

\[ q = 0.207 \text{ m}^3/\text{s}, \text{door} \times 3\text{secs open} \times 160 \text{ times opens in a day} = 99.36 \text{ m}^3 \text{ air} \]

<table>
<thead>
<tr>
<th></th>
<th>( T_{ext} )</th>
<th>( \nu_{out} )</th>
<th>( \nu_{door} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>-8.90</td>
<td>1.739</td>
<td>0.290</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.408</td>
<td>0.401</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2.13</td>
<td>3.776</td>
<td>0.629</td>
</tr>
<tr>
<td></td>
<td>-6.50</td>
<td>1.772</td>
<td>0.295</td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td>3.569</td>
<td>0.595</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
<td>2.877</td>
<td>0.480</td>
</tr>
<tr>
<td></td>
<td>-15.60</td>
<td>0.8903</td>
<td>0.148</td>
</tr>
<tr>
<td></td>
<td>5.9</td>
<td>3.810</td>
<td>0.635</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
<td>2.516</td>
<td>0.419</td>
</tr>
<tr>
<td></td>
<td>-19.7</td>
<td>0.6575</td>
<td>0.110</td>
</tr>
<tr>
<td></td>
<td>-2.6</td>
<td>1.769</td>
<td>0.295</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
<td>2.436</td>
<td>0.406</td>
</tr>
<tr>
<td></td>
<td>-17.8</td>
<td>0.7877</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>1.829</td>
<td>0.305</td>
</tr>
</tbody>
</table>

Table 13. Humidity content coming through the main door

- Building materials

The building materials may also have something to do with this generation. This will depend on the materials’ sorption and desorption curve. As it is a new building, it can happen that the building loses part of the moisture it has absorbed during a period of time (desorption). The difference between adsorption and desorption curves is called hysteresis.

The equilibrium moisture content for the material will depend on the moisture history of the material. Each material has its own sorption isotherm. All materials showing hardly any sorption are called non hygroscopic (bricks, insulation materials…). On the contrary, materials showing considerable sorption at low relative humidity are called hygroscopic (water-attracting) as for example cement bonded and timber based materials [22].

Nevertheless, this term will not be considered in the calculations.
Once all the parameters are known, the inside humidity can be calculated (*See Results chapter*).

**Dew point analysis**

It will be established at which temperature condensation will appear, this is,

\[ \nu_{\text{indoor}} = \nu_{\text{sat}}(T_{\text{surf}}) \]

for the average monthly conditions.

By making use of the psychrometric chart, the different air conditions will be located, being able then to determine the dew temperature at that humidity by reading the value once the saturation line is crossed.

A table with these results will be shown in ‘Results’ chapter (*See Table*).
6. RESULTS

6.1 Hand-made results

Energy balance

According to the previous energy balance, the temperature indoors can be obtained. It will be calculated for the following cases:
- Mean monthly outdoor temperature for October, November, December, January and February.
- Monthly coldest temperature for October, November, December, January and February.
- A sunny day within the month for October, November, December, January and February.

The results are shown in the following table:

<table>
<thead>
<tr>
<th></th>
<th>T outdoors (ºC)</th>
<th>T indoors (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temp</td>
<td>5.16</td>
<td>10.99</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-8.90</td>
<td>-1.64</td>
</tr>
<tr>
<td>Sunny day</td>
<td>2</td>
<td>9.75</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temp</td>
<td>2.13</td>
<td>7.42</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-6.50</td>
<td>0.22</td>
</tr>
<tr>
<td>Sunny day</td>
<td>6.1</td>
<td>13.62</td>
</tr>
<tr>
<td>DECEMBER</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temp</td>
<td>-1.37</td>
<td>4.56</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-15.60</td>
<td>-6.38</td>
</tr>
<tr>
<td>Sunny day</td>
<td>5.9</td>
<td>11.91</td>
</tr>
<tr>
<td>JANUARY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temp</td>
<td>-2.59</td>
<td>3.84</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-19.70</td>
<td>-9.72</td>
</tr>
<tr>
<td>Sunny day</td>
<td>-2.6</td>
<td>6.36</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean temp</td>
<td>-2.97</td>
<td>4.51</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-17.80</td>
<td>-8.87</td>
</tr>
<tr>
<td>Sunny day</td>
<td>-2</td>
<td>11.92</td>
</tr>
</tbody>
</table>

Table 14. Indoor temperatures
The temperature above calculated will refer to the average temperature indoors. Nevertheless, as it is known, warm air will move upwards the staircase making the temperature differ for the different floors. According to the experimental measures taken, it will be established that temperature is 0.2°C higher each floor.

*Tindoors (average) = T (8th floor)*

<table>
<thead>
<tr>
<th></th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
<th>6th</th>
<th>7th</th>
<th>8th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov mean</td>
<td>6.22</td>
<td>6.42</td>
<td>6.62</td>
<td>6.82</td>
<td>7.02</td>
<td>7.22</td>
<td>7.42</td>
</tr>
<tr>
<td>Dec mean</td>
<td>3.36</td>
<td>3.56</td>
<td>3.76</td>
<td>3.96</td>
<td>4.16</td>
<td>4.36</td>
<td>4.56</td>
</tr>
<tr>
<td>Jan mean</td>
<td>2.64</td>
<td>2.84</td>
<td>3.04</td>
<td>3.24</td>
<td>3.44</td>
<td>3.64</td>
<td>3.84</td>
</tr>
<tr>
<td>Feb mean</td>
<td>3.31</td>
<td>3.51</td>
<td>3.71</td>
<td>3.91</td>
<td>4.11</td>
<td>4.31</td>
<td>4.51</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>9th</th>
<th>10th</th>
<th>11th</th>
<th>12th</th>
<th>13th</th>
<th>14th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov mean</td>
<td>7.62</td>
<td>7.82</td>
<td>8.02</td>
<td>8.22</td>
<td>8.42</td>
<td>8.62</td>
</tr>
<tr>
<td>Dec mean</td>
<td>4.76</td>
<td>4.96</td>
<td>5.16</td>
<td>5.36</td>
<td>5.56</td>
<td>5.76</td>
</tr>
<tr>
<td>Jan mean</td>
<td>4.04</td>
<td>4.24</td>
<td>4.44</td>
<td>4.64</td>
<td>4.84</td>
<td>5.04</td>
</tr>
<tr>
<td>Feb mean</td>
<td>4.71</td>
<td>4.91</td>
<td>5.11</td>
<td>5.31</td>
<td>5.51</td>
<td>5.71</td>
</tr>
</tbody>
</table>

Table 15. Distribution of temperatures

According to the moisture transfer above explained, the following window surface temperatures are obtained. Next to the surface temperature calculated, it will also be displayed the humidity at saturation for that temperature.

<table>
<thead>
<tr>
<th></th>
<th>Tout (°C)</th>
<th>Tint (°C)</th>
<th>P (W/m²)</th>
<th>Tsurf (°C)</th>
<th>vsat (Tsurf) (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temp</td>
<td>5.16</td>
<td>10.99</td>
<td>33.231</td>
<td>6.67</td>
<td>6.072</td>
</tr>
<tr>
<td>Mean temp (2nd)</td>
<td>5.16</td>
<td>9.79</td>
<td>26.391</td>
<td>6.36</td>
<td>5.949</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-8.90</td>
<td>-1.64</td>
<td>41.382</td>
<td>-7.02</td>
<td>2.291</td>
</tr>
<tr>
<td>Sunny day</td>
<td>2</td>
<td>9.75</td>
<td>44.175</td>
<td>4.01</td>
<td>5.087</td>
</tr>
</tbody>
</table>

5 Based on the experimental data
<table>
<thead>
<tr>
<th>NOVEMBER</th>
<th>Tout (ºC)</th>
<th>Tint (ºC)</th>
<th>P (W/m²)</th>
<th>Tsurf (ºC)</th>
<th>vsat (Tsurf) (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temp</td>
<td>2,13</td>
<td>7,42</td>
<td>30,153</td>
<td>3,50</td>
<td>4,917</td>
</tr>
<tr>
<td>Mean temp (2º)</td>
<td>2.13</td>
<td>6.22</td>
<td>23,313</td>
<td>3,19</td>
<td>4,814</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-6,50</td>
<td>0.22</td>
<td>38,304</td>
<td>-4,76</td>
<td>2,761</td>
</tr>
<tr>
<td>Sunny day</td>
<td>6.1</td>
<td>13.62</td>
<td>42,864</td>
<td>8,05</td>
<td>6,643</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DECEMBER</th>
<th>Tout (ºC)</th>
<th>Tint (ºC)</th>
<th>P (W/m²)</th>
<th>Tsurf (ºC)</th>
<th>vsat (Tsurf) (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temp</td>
<td>-1.37</td>
<td>4.56</td>
<td>33,801</td>
<td>0,17</td>
<td>3,911</td>
</tr>
<tr>
<td>Mean temp (2º)</td>
<td>-1.37</td>
<td>3.36</td>
<td>26,961</td>
<td>-0,14</td>
<td>3,827</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-15.60</td>
<td>-6.38</td>
<td>52,554</td>
<td>-13,21</td>
<td>1,353</td>
</tr>
<tr>
<td>Sunny day</td>
<td>5.9</td>
<td>11.91</td>
<td>34,257</td>
<td>7,46</td>
<td>6,393</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>JANUARY</th>
<th>Tout (ºC)</th>
<th>Tint (ºC)</th>
<th>P (W/m²)</th>
<th>Tsurf (ºC)</th>
<th>vsat (Tsurf) (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temp</td>
<td>-2.59</td>
<td>3.84</td>
<td>36,651</td>
<td>-0,92</td>
<td>3,511</td>
</tr>
<tr>
<td>Mean temp (2º)</td>
<td>-2.59</td>
<td>2.64</td>
<td>29,811</td>
<td>-1,24</td>
<td>3,67</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-19.70</td>
<td>-9.72</td>
<td>56,886</td>
<td>-17,12</td>
<td>0,959</td>
</tr>
<tr>
<td>Sunny day</td>
<td>-2.6</td>
<td>6.36</td>
<td>51,072</td>
<td>-0,28</td>
<td>3,96</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FEBRUARY</th>
<th>Tout (ºC)</th>
<th>Tint (ºC)</th>
<th>P (W/m²)</th>
<th>Tsurf (ºC)</th>
<th>vsat (Tsurf) (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean temp</td>
<td>-2.97</td>
<td>4.51</td>
<td>42,636</td>
<td>-1,03</td>
<td>3,479</td>
</tr>
<tr>
<td>Mean temp (2º)</td>
<td>-2.97</td>
<td>3.31</td>
<td>35,796</td>
<td>-1,34</td>
<td>3,638</td>
</tr>
<tr>
<td>Coldest temp</td>
<td>-17.80</td>
<td>-8.87</td>
<td>50,901</td>
<td>-15,49</td>
<td>1,108</td>
</tr>
<tr>
<td>Sunny day</td>
<td>-2</td>
<td>11.92</td>
<td>79,344</td>
<td>1,61</td>
<td>4,321</td>
</tr>
</tbody>
</table>

Table 16. Surface temperatures and humidity at saturation

On the other hand, the following table shows the results obtained for the humidity content indoors according to what explained in the 'moisture transfer’ chapter.
If the results obtained for both $v_{sat}$ ($T_{surf}$) and $v_{in}$ are now compared, it can be seen that, the psychrometric conditions in the window were found to be near Dew Point most of the time. Indeed in every month, condensation will occur because the humidity inside is much higher than the saturation humidity.

The following table shows the dew point temperature for the average monthly cases.

<table>
<thead>
<tr>
<th></th>
<th>$T$ outdoors (°C)</th>
<th>$v_{in}$ (g/kg)</th>
<th>$T$ Dew Point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>10.99</td>
<td>6.118</td>
<td>6.69</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>7.42</td>
<td>5.158</td>
<td>4.26</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>4.56</td>
<td>4.061</td>
<td>0.91</td>
</tr>
<tr>
<td>JANUARY</td>
<td>3.84</td>
<td>3.630</td>
<td>-0.55</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>4.51</td>
<td>3.549</td>
<td>-0.82</td>
</tr>
</tbody>
</table>

Table 18. Dew point temperatures

Condense will appear when the glass surf temp is lower than the dew point of the surrounding air, this is, when the inside temperature equals or is lower than the dew point temperature. According to the values obtained, for the average cases condensation will appear in all of them as the temperature of the surface is lower than the dew point.
temperature. The problem is even worse when condensation appears for temperatures below zero because the condensate will freeze, which will longer the effect of the saturation.

As the result of data analysis shows, the relative humidity of the ambient air is quite high (Figure below), which means a high potential for condensation the moment the temperature drops slightly.

![Figure 47. RH of exterior and interior air](image)

Once dew point temperatures have been established, it can be determined the outdoor temperature limit at which condensation will start to occur. This effect can be appreciated in the following chart which enables to read the outdoor temperature at which condensation on the window surface will start for the average monthly conditions studied.

![Figure 48. Outdoor temperature at condensation for the different months analyzed](image)
6.2 Results with IDA

After building the model in IDA and defining the type of walls, leakages, ventilation… the following results were obtained for Gävle’s climate.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean air temperature, Deg.C</th>
<th>Operative temperature, Deg.C</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>-1.6</td>
<td>-0.3</td>
</tr>
<tr>
<td>February</td>
<td>-1.8</td>
<td>-2.0</td>
</tr>
<tr>
<td>March</td>
<td>5.0</td>
<td>4.9</td>
</tr>
<tr>
<td>April</td>
<td>14.4</td>
<td>14.9</td>
</tr>
<tr>
<td>May</td>
<td>19.2</td>
<td>20.1</td>
</tr>
<tr>
<td>June</td>
<td>29.9</td>
<td>26.5</td>
</tr>
<tr>
<td>July</td>
<td>27.5</td>
<td>28.1</td>
</tr>
<tr>
<td>August</td>
<td>27.9</td>
<td>28.4</td>
</tr>
<tr>
<td>September</td>
<td>17.1</td>
<td>17.2</td>
</tr>
<tr>
<td>October</td>
<td>10.9</td>
<td>10.8</td>
</tr>
<tr>
<td>November</td>
<td>7.5</td>
<td>7.3</td>
</tr>
<tr>
<td>December</td>
<td>3.4</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The results obtained meet the expectations, as they match the temperature obtained with the hand-made results for almost every month analyzed. There are some discrepancies that could be due to some missing information in the IDA model.

The surface temperature on the window can also be observed in the following chart.

![Figure 49. Monthly indoor temperatures with IDA](image)

The tendency of the relative humidity indoors obtained for the IDA model can be observed in the following Figure, which mostly matches with the results obtained.
Figure 51. RH indoors with IDA
7. ANALYSIS FOR 2 PANE WINDOW CONSIDERATION

Most double glazed windows currently manufactured consist of two panes of glass separated from each other by an edge-seal. The edge-seal isolates the cavity between the glazings, thereby creating an enclosure suitable for non-durable coatings and/or substitute infill gases.

It should be emphasized that good thermal insulation improves energy efficiency directly by lowering the U-value. Additionally, it lowers indirectly the heating requirements by raising the inner surface temperature close to room air temperature. The set-point temperature of a heating system may be lowered by 1-2 degree according to the area of glazing without reducing comfort [6].

In addition to reducing energy loss from buildings, 2 pane windows also offer the following advantages:
- The improvement of comfort through the elimination of cold downdraughts and radiation exchange.
- Excellent noise attenuation performance.
- An increase in the total light admission in residential and other buildings by allowing greater window areas to be employed without increasing the overall energy losses.
- Greater flexibility and freedom for architects, designers and users.
- A reduction in condensation problems at the window edge area.

The typical distribution of a 2 pane window can be seen in the following Figure.

![Figure 52. Two pane window configuration](image)

Now, the same analysis explained before for the real case will be studied for two pane windows. It must be highlighted that this analysis only aims to compare the results that would have been obtained if the window installed had this configuration and it that it is not an exact possible solution for the actual window. The solution that could be
implemented based on this principle would be adding a secondary glazing as it would be explained in ‘Solutions’ Chapter.

The only components of the balance that change are the sun radiation effect and the losses through the new window. As the window has an air gap, convection will have its influence now. Moreover, if a low $\varepsilon$-coating is included, there will be radiation also. The low- $\varepsilon$ coating would reflect the long wave radiation, heat, back into the staircase.

Figure 53. Two pane window with low $\varepsilon$ coating

The modifications could be described as followed:

$$Q'_{\text{radiation}} = g' \times A \times I_{\text{sun}}$$

$g' = 0.74$ for the 2 pane window considered (See Appendix 4).

$$Q'_{\text{window}} = U'_{\text{window}} \times A \times \Delta T$$

The new $U'$-value for the 2 pane window will be 2.8 W/m$^2$ K (See Appendix 4).

7.1 Hand-made results

As it can be seen from the results below, when adding a secondary pane, the inside temperature will increase, making increase the temperature on the inner surface of the window and thus, reducing the risk of condensation.
<table>
<thead>
<tr>
<th></th>
<th>T outdoors (°C)</th>
<th>T indoors (°C)</th>
<th>T surface (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>5.16</td>
<td>11.69</td>
<td>9.31</td>
</tr>
<tr>
<td></td>
<td>-8.90</td>
<td>-0.36</td>
<td>-3.47</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2.13</td>
<td>8.3</td>
<td>6.05</td>
</tr>
<tr>
<td></td>
<td>-6.50</td>
<td>1.41</td>
<td>-1.47</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
<td>5.59</td>
<td>3.06</td>
</tr>
<tr>
<td></td>
<td>-15.60</td>
<td>-4.72</td>
<td>-8.68</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
<td>4.94</td>
<td>2.20</td>
</tr>
<tr>
<td></td>
<td>-19.7</td>
<td>-7.97</td>
<td>-12.24</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
<td>5.56</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>-17.8</td>
<td>-7.41</td>
<td>-11.19</td>
</tr>
</tbody>
</table>

Table 19. Inside temperature for 2 pane window

Thanks to the secondary glazing, the problem of condensation for the average monthly cases would be solved as the temperature of the surface is higher than dew point temperature. Nevertheless, the problem would remain when surface temperature drops below it, but this would be reduced to a much shorter time (*See table 16 of dew point temperatures in ‘Results’ Chapter*).

A good approach to deal with condensation when it cannot totally be eliminated is that the installation of pane frames with a draining unit. Thanks to this, when droplets form on the surface, they will drop before they freeze and could be drained to the exterior.

![Figure 54. Standard vs Drained glazing units](image)
7.2 Results with IDA

The modifications previously commented were introduced into IDA program. The new inside temperatures for the staircase obtained with IDA can be observed in the following table.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean air temperature, Deg C</th>
<th>Operative temperature, Deg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>February</td>
<td>-0.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>March</td>
<td>5.8</td>
<td>6.7</td>
</tr>
<tr>
<td>April</td>
<td>15.6</td>
<td>15.8</td>
</tr>
<tr>
<td>May</td>
<td>20.7</td>
<td>21.2</td>
</tr>
<tr>
<td>June</td>
<td>27.0</td>
<td>27.7</td>
</tr>
<tr>
<td>July</td>
<td>28.6</td>
<td>29.3</td>
</tr>
<tr>
<td>August</td>
<td>28.8</td>
<td>29.3</td>
</tr>
<tr>
<td>September</td>
<td>18.0</td>
<td>18.2</td>
</tr>
<tr>
<td>October</td>
<td>11.9</td>
<td>13.9</td>
</tr>
<tr>
<td>November</td>
<td>8.5</td>
<td>8.4</td>
</tr>
<tr>
<td>December</td>
<td>4.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Mean*8764.0 h</td>
<td>124369.6</td>
<td>125798.6</td>
</tr>
<tr>
<td>min</td>
<td>-0.8</td>
<td>-0.9</td>
</tr>
<tr>
<td>max</td>
<td>28.8</td>
<td>29.3</td>
</tr>
</tbody>
</table>

Table 20. Results with IDA software for 2 pane window

The results obtained are quite similar to those obtained by hand-made calculations. They validate the results obtained although they may vary a little bit for some months.

7.3 Considering a triple pane window

Observing the results obtained for 2 pane windows it could be thought if installing 3 pane windows would be worthy. In order to see if this investment would be worthy, the outward heat flow through the window will be studied; this is, the heat loss through the window minus the sun radiation entering through it.

To do so, the inside temperature for the case of three panes must be calculated. For this case, the properties are obtained from the data sheet of the manufacturer (See Appendix 5).

<table>
<thead>
<tr>
<th>T outdoors (°C)</th>
<th>T indoors (°C)</th>
<th>T surface (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>5.16</td>
<td>11.96</td>
</tr>
<tr>
<td>November</td>
<td>2.13</td>
<td>8.64</td>
</tr>
<tr>
<td>December</td>
<td>-1.37</td>
<td>5.99</td>
</tr>
<tr>
<td>January</td>
<td>-2.59</td>
<td>5.36</td>
</tr>
<tr>
<td>February</td>
<td>-2.97</td>
<td>5.96</td>
</tr>
</tbody>
</table>

Table 21. Indoor temperature for a 3 pane window
\[ Q = \text{Heat loss} - \text{Sun radiation} = U \times A \times \Delta T - g \times A \times I_{\text{sun}} \ (W) \]

<table>
<thead>
<tr>
<th></th>
<th>October</th>
<th>November</th>
<th>December</th>
<th>January</th>
<th>February</th>
</tr>
</thead>
<tbody>
<tr>
<td>1pane</td>
<td>84.62</td>
<td>2399.53</td>
<td>3331.80</td>
<td>3146.18</td>
<td>1863.86</td>
</tr>
<tr>
<td>2panes</td>
<td>-944.91</td>
<td>1112.51</td>
<td>1783.74</td>
<td>1548.94</td>
<td>265.58</td>
</tr>
<tr>
<td>3panes</td>
<td>-1346.8</td>
<td>608.19</td>
<td>1160.92</td>
<td>920.91</td>
<td>-356.15</td>
</tr>
</tbody>
</table>

Table 22. Comparison of outward heat flow

From the results obtained it can be seen that even installing 3 pane windows would be worthy from a thermal point of view as it stills reduces considerably the outward heat flow but the effect of adding a second pane is much considerable that adding a third one.

These changes will also influence the outdoor temperature at which condensation inside will appear. For example, the case of the month of October will be studied. In the following chart the dew point temperature for October (6.69°C) has been established.

<table>
<thead>
<tr>
<th>T outdoor (ºC)</th>
<th>Condensation forms</th>
</tr>
</thead>
<tbody>
<tr>
<td>-4.00</td>
<td></td>
</tr>
<tr>
<td>-3.00</td>
<td></td>
</tr>
<tr>
<td>-2.00</td>
<td></td>
</tr>
<tr>
<td>-1.00</td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td></td>
</tr>
<tr>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td></td>
</tr>
</tbody>
</table>

Table 23. Outdoor temperature at condensation for single, double and triple pane windows for October

From the chart it can be seen how for the single pane window, condensation will occur for outside temperatures below 5.3°C; whereas for a 2 pane window this temperature would be 2.45°C and for a triple one, 1.2°C.
Savings:
To calculate the savings that could be obtained by adding panes, it will be supposed that the staircase is provided with hydronic space heating, this is, a radiator connected to the district heating system running the whole day. The radiator would be used to reach the objective temperature to avoid condensation. This means that it uses the DHS average rate of 0.4545kr/kWh, so the daily cost would be 10.91kr/kW each day (1.27€/kW).

The following table shows the cost savings that could be achieved if adding a second or third pane.

<table>
<thead>
<tr>
<th></th>
<th>1 pane to 2 panes</th>
<th>1 pane to 3 panes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Q reduction (W)</strong></td>
<td>€ savings</td>
<td><strong>Q reduction (W)</strong></td>
</tr>
<tr>
<td>October</td>
<td>1029.53</td>
<td>40.53</td>
</tr>
<tr>
<td>November</td>
<td>1287.02</td>
<td>49.04</td>
</tr>
<tr>
<td>December</td>
<td>1548.06</td>
<td>60.95</td>
</tr>
<tr>
<td>January</td>
<td>1597.24</td>
<td>62.88</td>
</tr>
<tr>
<td>February</td>
<td>1598.28</td>
<td>60.89</td>
</tr>
<tr>
<td><strong>TOTAL WINTER</strong></td>
<td><strong>7060.13</strong></td>
<td><strong>274.29</strong></td>
</tr>
</tbody>
</table>

Table 24. Savings by adding panes

Once the savings are determined, an analysis should be made to compare if the investment of adding a second or third layer would be lower than the investment in the radiators plus their energy use.
8. SOLUTIONS

Condensation is very much related to the way in which buildings are heated, ventilated and insulated. In any consideration of the thermal performance of a building shell, it is essential to consider condensation as a very vital factor because in extreme circumstances, it may cause structural collapse.

Two generic types of remedial measures are available for combating condensation: those which increase mean internal temperature and those designed to reduce internal vapor pressure. By control of temperature and air movement, much of the inconvenience of condensation can be prevented.

With the first category, high surface temperatures could be obtained by providing more insulation and/or increasing the heat input. On the other hand, the second category will make it possible to obtain low vapor pressures by ventilation and/or reduced moisture input to the building.

8.1 Increasing temperature

8.1.1 Secondary Glazing

Fixed secondary glazing units are simply manufactured as a single pane glazed panel that is fixed direct to existing windows. It is a way to convert the single pane window into a two pane one, achieving with it its benefits. They provide advantages as reducing noise levels, excluding draughts and minimizing heat loss. While being practical it is also one of the most aesthetically pleasing systems, with slim and discrete features to minimize its impact on the interior. Adding well fitted secondary glazing with ordinary 4mm glass will give significant benefits in energy saving and reducing condensation.
Recent research has shown heat losses by conduction and radiation through a window as a whole can be reduced by over 60% by using secondary glazing with a low emissivity (low-\(\varepsilon\)) hard coating facing the outside. Specifying ‘K’ glass, which has a special heat reflecting coating, gives an extra improvement over un-coated glass and helps to keep the heat in the room. The research has also shown that further savings can be made if the secondary glazing uses insulating frames [23].

Calculations:

For thermal performance, the optimum airspace between panes is 16 – 20 mm. A larger air space allows convection currents to develop within the cavity and more heat to be lost. The positioning of the secondary unit is usually dictated by the window reveal and can often only be fitted at a distance of about 100 mm from the primary glazing. The U-value for this disposition is set at 3.2W/m\(^2\)K [24].
According to this description the heat losses through the window will be decreased in a 43.86%. As a drawback, the sun radiation through the window would also be decreased. Nevertheless, in the months of interest (winter) this will not highly affect the temperature as the sun radiation is already low [25].

8.1.2 Electrically heated window pane

In order to electrically heat glass, a microscopic Tin (II) Oxide coating is applied to a pane of ordinary float glass. This coating is perfectly transparent and conducts electricity. An electrical current is supplied by two busbars located on opposite sides of the glass. The electrical resistance of the Tin Oxide coating produces heat energy. This heat radiates from the glass in the form of infrared energy. The busbars are typically connected to a power control unit that regulates the flow of electricity and thus the temperature of the glass. A temperature control unit is mounted on the film and is housed in an aluminum enclosure.

Electrically heated glass maintains a steady and consistent temperature across the entire surface, and heat radiates off the glass in only one direction: toward the object or area to be heated [26].

Figure 57. Principle of electrically heated window

The efficiency of a common heated window with a $U$-value of 1.1 W/m$^2$ K has been set about 78% at an outdoor temperature of −10 °C. Efficiency was proportional to the outdoor temperature and practically independent of the inner surface temperature of the window, the effect of which was less than 1%.\footnote{Energy and Buildings. Volume 36, Issue 10, October 2004, Pages 1003–1010, REHVA Scientific, Elsevier}

The glass selected would be from the same brand as the current window, Saint-Gobain Thermovit Elegance, which has the following specifications.
ELECTRICAL SPECIFICATIONS [27]

All electrical specifications are in direct dependence to the size and aspect ratio of the film. With sheet resistance being stable, power will diminish as the sheet size becomes larger.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>100-120 VAC</th>
<th>210-240 VAC</th>
<th>100-120 VAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amperage</td>
<td>Up to 3.5</td>
<td>Up to 2.5</td>
<td>Up to 3.5</td>
</tr>
</tbody>
</table>

Table 25. Electrical specifications of the film

The maximum capacity for each glass is 3600W.

OPTICAL SPECIFICATIONS [27]

<table>
<thead>
<tr>
<th>Thickness</th>
<th>6 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total visible transmittance</td>
<td>72%-85%</td>
</tr>
<tr>
<td>Hardcoated total visible reflectance</td>
<td>13%-18%</td>
</tr>
</tbody>
</table>

Table 26. Optical specifications of the film

The installation would consist of 73 panels of 80 W each, located between the frames.

If the term of the power provided by the resistance is added now to the energy balance, and a power of 50W/m² is supposed, the new indoor temperature could be known.

<table>
<thead>
<tr>
<th>T outdoors (ºC)</th>
<th>T indoors (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>5.16</td>
</tr>
<tr>
<td></td>
<td>13.71</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2.13</td>
</tr>
<tr>
<td></td>
<td>10.13</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
</tr>
<tr>
<td></td>
<td>7.25</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
</tr>
<tr>
<td></td>
<td>6.53</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
</tr>
<tr>
<td></td>
<td>7.17</td>
</tr>
</tbody>
</table>

Table 27. Indoor temperatures with heated glass

As it can be observed from the results, the increase in the temperatures is highly significant and would reduce condensation in almost every hour. Indeed, as the heat source is directly placed on the window, condensation will never occur on this surface.

Comparing these temperatures with the dew temperatures calculated before for the indoor moisture content, it can be seen that this solution keeps the condition of the
window far from condensation. It can also be contrasted with the saturation humidity at these temperatures.

<table>
<thead>
<tr>
<th></th>
<th>T outdoors (ºC)</th>
<th>T indoors (ºC)</th>
<th>vsat (Tin) (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>5,16</td>
<td>13,71</td>
<td>9,84</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2,13</td>
<td>10,13</td>
<td>7,75</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
<td>7,25</td>
<td>6,361</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
<td>6,53</td>
<td>6,051</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
<td>7,17</td>
<td>6,325</td>
</tr>
</tbody>
</table>

**Table 28. Humidity content at saturation**

As it can be seen from the table, the saturation humidity is higher than the actual humidity content for both the average and the coldest cases, so there would be no risk for condensation.

**Cost:**

Besides the investment, the cost of its energy use could be obtained. If it is supposed that the resistances were connected during the number of hours that outside temperature is below the outside temperature at which condensation would start (See Figure 49) the energy use can be known. The results obtained can be seen in the following Table.

<table>
<thead>
<tr>
<th>Limit Temperature (ºC)</th>
<th>Power (W)</th>
<th>Nº hours below T limit (h)</th>
<th>Energy (kWh)</th>
<th>Cost (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October</td>
<td>5.35</td>
<td>353</td>
<td>2100</td>
<td>220</td>
</tr>
<tr>
<td>November</td>
<td>2.8</td>
<td>410</td>
<td>2400</td>
<td>250</td>
</tr>
<tr>
<td>December</td>
<td>-0.65</td>
<td>353</td>
<td>2100</td>
<td>220</td>
</tr>
<tr>
<td>January</td>
<td>-2.2</td>
<td>355</td>
<td>2100</td>
<td>220</td>
</tr>
<tr>
<td>February</td>
<td>-2.5</td>
<td>370</td>
<td>2200</td>
<td>235</td>
</tr>
</tbody>
</table>

**Table 29. Energy price of running the panels**

It should be mentioned that to reduce the cost and reach the temperature limit to avoid condensation, it wouldn’t be needed to connect all the panels the whole time. Their power could be regulated to obtain just the dew point temperature when it is necessary.

---

8 Approximate values
9 According to the electricity average rate of 10.75cents/kWh for a unit of electricity (Gävle Energi AB)
8.1.3 Secondary film

This solution is based on the following principle:

« Not too much glazing but well glazed ».

The main reason for this is that a glazing surface is about three times the cost of an insulated wall.

a) Energy film

This film is based on solar control functioning. The implementation of this film will be less effective than the last method, but thanks to the nano-particles in the film it will retain part of the heat inside the building, decreasing the heat losses. This effect can be observed in the following Figure [28].

![Figure 58. Heat transfer without and with energy film](image)

![Figure 59. Properties of the Energy film](image)

Cost:

According to ‘Energy Film’ company, a film of 1.22x2.15 m would cost 35.6€. Taking into account the window surface, 48 rolls would be needed. This would mean an investment of 1710€.
b) **Moniflex**

Moniflex is an environmental friendly product made of natural cellulose polymers. The product is constructed of Crosswise glued, pleated cellulose foil with a small amount of fire retardant added. Its physical appearance can be observed in the following picture [29].

![Figure 60. Moniflex film](image)

This secondary film would work as a second pane but attached to the initial one and made of cellulose instead of glass. Due to its construction, Moniflex is the perfect film when condensation is involved as it drains off condensed water and maintains its insulation properties even if affected by high humidity.

As the manufacturer provides, a 20 mm thick Moniflex layer has a thermal conductivity of 0.0541W/mK. If this film was to be installed, it would decrease the heat losses through the window in a 67.8% (U’value=1.834W/m²K).

Nevertheless, the heat gains due to radiation would also be decreased and the light transmittance could also be affected. Its main drawback would be that it highly disturbs visibility.

c) **Solar Gard Ecolux (Saint Gobain): Low ε coatings**

A glazing design for maximizing energy efficiency during underheated periods would ideally allow all of the solar spectrum to pass through, but would block the re-radiation of heat from the inside of the space.

A key concept to improving window energy efficiency is therefore spectral selectivity, implying that the radiative properties should be qualitatively different for different wavelength ranges, so that, for example, it is possible to combine high transmittance of luminous radiation with reflection of thermal radiation. Based on this principle, this kind of films not only prevents solar radiation from entering solar control glass does, but also reduces thermal losses [30].
In this way, low-\(\varepsilon\) coatings were designed to have a high solar heat gain coefficient and a high visible transmittance to allow the maximum amount of sunlight into the interior while reducing the U-factor significantly.

![Figure 61. Clear glass vs glass with low-emittance coatings](image)

Materials absorb radiation from other sources and reradiate them at lower wavelengths. Low-E materials are based on the principle of emitting less radiant energy, this is, plastic films that contain metal or metal oxide with high transmittance in the visible (400-800 nm) and low transmittance in the Near Infrared (800-2500 nm).

![Figure 62. Spectral wavelengths](image)

However, while providing excellent cooling season savings, these window films often suffer from one drawback, in that they reduce solar gain through windows all year long, even when such heat gain may be desired (as during the heating season). So, these films may actually increase the amount of heat that must be supplied by the building’s heating system. The gain of free solar heat during winter typically is not a large amount, as during winter there are considerably more days with cloudy weather and the hours of daylight during winter are less than during summer.
Properties:

As it can be seen in the manufacturer data sheet (See Appendix 6), if this low-\(\varepsilon\) film (\(\varepsilon = 0.07\)) is applied to the existing glass, it would be able to reduce the U-value to 0.59 W/m\(^2\)K.

d) Comparison

The following table gathers and compares the main parameters for the films explained above.

<table>
<thead>
<tr>
<th></th>
<th>Energy film</th>
<th>Moniflex</th>
<th>Low-(\varepsilon)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Heat Gain</td>
<td>0.52</td>
<td>-</td>
<td>0.24</td>
</tr>
<tr>
<td>Visible light transmittance</td>
<td>77%</td>
<td>-</td>
<td>31%</td>
</tr>
<tr>
<td>U'-value (W/m2K)</td>
<td>-</td>
<td>1.834</td>
<td>0.59</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.15</td>
<td>20</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 30. Comparison between window films

8.1.4 Considering Emerging Technologies(Building applied Photovoltaics (BAPV))

This is a recently patented\(^{10}\) system that allows a high degree of light transmission while generating electricity from a reduced area of expensive photovoltaic material using a novel high efficiency concentrator design. PV cells are typically opaque, which prevented the light transmission. Nevertheless, thanks to this new ‘Solar Window’ concept, this problem is solved, decreasing at the same time the cost of the cells as they contain a smaller surface of PV cells [31].

\(^{10}\) Herriot Watt University, UK.
The main problem with this technology is that as they depend on the sun radiation, and this is not Sweden’s strongest point.

8.1.5 Adding a radiator

Installation of heating equipment has a significant impact on thermal comfort conditions in rooms. It depends on thermal properties of the window, heat load emitted by the heating device as well as the geometry of the windowsill.

In principle, heating should be understood as mere warming of the air. In the psychrometric it is displayed horizontally as dry heating. The air in its original state warms up and the relative air humidity drops. Absolute humidity remains the same; no water is added or extracted.

To minimize surface condensation the duration and amount of heating could be regulated to maintain the internal surface temperature above dew point.

As the staircase is not an inhabited space, the comfort of the occupants could be ignored. Thus, the aim should be to maintain an air temperature at or above 12°C to 15°C in all parts of the building that are heated.

An air heater installed on the base floor would indeed decrease the effect of the downdraught.

Design of the radiator

The hypothesis that will be followed is that the temperature on the eight floor (average temperature for the staircase) is 12 °C so that the lower floors don’t get too cool.

If the energy balance is now posed, the power of the radiator can be known.

\[ Q_{wall \text{-}rooms} + Q_{floor} + Q_{radiation} + Q_{radiator} = Q_{roof} + Q_{window} + Q_{walls} + Q_{vent} \]

All the terms that take part in the energy balance will be the same as for the initial case.
According to the values obtained above, the power provided by the radiator of around 25 kW could be installed to obtain the expected results for a sufficient period of time, even if it is known that it will not be able to reach the desired temperature inside in some particular cases.

It could be selected, according to the table below, 10 electric radiators of double panel with fins with dimensions of 1200mm x 600 mm for ten floors, obtaining a power of 2.2kW per radiator.

<table>
<thead>
<tr>
<th></th>
<th>T outdoors (°C)</th>
<th>Q radiator (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTOBER</td>
<td>5.16</td>
<td>2.15</td>
</tr>
<tr>
<td></td>
<td>-8.90</td>
<td>31.81</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>2.13</td>
<td>9.94</td>
</tr>
<tr>
<td></td>
<td>-6.50</td>
<td>27.19</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>-1.37</td>
<td>16.4</td>
</tr>
<tr>
<td></td>
<td>-15.60</td>
<td>42.02</td>
</tr>
<tr>
<td>JANUARY</td>
<td>-2.59</td>
<td>18.05</td>
</tr>
<tr>
<td></td>
<td>-19.7</td>
<td>51.21</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>-2.97</td>
<td>16.68</td>
</tr>
<tr>
<td></td>
<td>-17.8</td>
<td>19.75</td>
</tr>
</tbody>
</table>

**Table 31. Radiator power for different cases**

The cost running of the radiator will depend on the time it is kept working. It must be mentioned that the radiator power is set to cover the average heat necessary. Nevertheless if the power is regulated for each month in particular, some savings could be obtained.

---

\[11\] Power in Watts
Also, if the type of radiator would be hydronic, the energy cost could be lower if it would be connected to the district heating grid.

8.2 Decreasing air humidity

8.2.1 Higher ventilation

One principle of good design for natural ventilation is to 'build tight - ventilate right'. A building cannot be 'too tight', but it can be under-ventilated.

As mentioned before, two holes were drilled on the wall in a desperate way to avoid the condensation problem. This was thought so as to disperse the internal moisture laden air and replace it with drier air from outside as external air is drier than internal air most of the year.

Nevertheless, this measure to have natural ventilation due to the stack effect has not been enough to stop condensation from appearing.

The problem of increasing ventilation is that there is greater heat lost by ventilation to be replaced which means that the temperature in the volume considered will decrease. Ventilation can be achieved by opening a few windows, installing air vents, and using extractor fans. However, it is most effective to remove the water vapor from where it is usually generated, in this case, from the apartments.

This is achieved by the installation of a powered extractor fan. Better still, rather than making the occupant responsible for operating the fan, a humidistat controlled unit can be used. These activate when moisture levels in the atmosphere reach a point at which they may begin to cause a problem [32].

Another approach, should condensation be widespread, is to use a ‘positive pressure system’ such as the PPF9 Positive Pressure System available from Safeguard Company. This consists of a slow speed fan set into the ceiling. It draws air into the roof space from outside through the eaves, and gently pushes it into the property. This causes a slight internal positive pressure, continually pushing out any moisture laden air as it develops. Nevertheless, this method would affect negatively making the temperature decrease if no preheating of the air is considered [32].
8.2.2 Air-conditioning

The most common method to change air humidity levels is air-conditioning. Air-conditioning systems regulate temperature and air humidity within a predefined range throughout the entire year. In combination with heating and cooling registers, they can continuously influence the condition of the air.

Fresh supply air would be sucked in from the outside through a piping network. After conditioning, the air would be blown through ducts into the room. Exhaust air is extracted through an additional piping network and is reconditioned in the air-conditioning unit (ACU).

These units remove water from the atmosphere, lower the water content of air, and therefore lower the risk of condensation.

Figure 65. Working principle of ACU

As condensation is due to excess moisture in air, the idea of the implementation of a dehumidifier could be great. Nevertheless, if the space being dehumidified has temperatures that typically fall below 18°C, a product that is specified for use at lower temperatures should be considered.

Figure 66. Principle of dehumification
Frost can form on the condensing coils and negatively affect the performance of the product by causing the compressor to cycle on and off repeatedly without removing moisture from the air. Qualified ENERGY STAR models are available that are rated for use at temperatures as low as 5.5°C. This is not enough for the problem being studied if dehumidifiers were thought to be installed in the staircase, and thus this idea should be rejected. Another option would be to install dehumidifiers in the areas that connect the apartments to the staircase, as it is the opening of those doors the main source of humidity into the staircase.

If really cold climates are considered as it is Gävle’s case, another option would be to integrate enthalpy wheels as a part of an air-conditioning system [33]. An enthalpy wheel can be described as a large, turning disc made out of an aluminum honeycomb material that is coated in desiccant\(^\text{12}\).

![Figure 67. Arrangement of an enthalpy wheel](image)

In addition to using sensible energy, an enthalpy wheel helps to exploit the thermal energy that is stored in the air humidity as latent heat. They are used to recover thermal energy that is stored in water vapor as latent thermal energy. The surface of an enthalpy wheel is hygroscopic promoting humidity transfer. It would retain the humidity contained in the air. In this case, the cold climate won’t be a problem because during extremely cold winter conditions, exhaust air stream frost formation becomes a possibility. Frost formation will act to plug or reduce air flow but it will not hurt the enthalpy wheel itself.

The main disadvantage of the enthalpy wheel is the initial capital expenditure for the product. It should also be noted that for optimal performance of the overall system, the

\(^{12}\text{QU, 2006}\)
enthalpy wheel requires two air streams be adjacent to each other which is not the current case.

8.2.3 Condensate trap in aluminum tubes

Last but not least, the condensate trap system is commented. The concept is based on the principle of a condensate trap; air with high humidity content strikes cold piping or wiring where the water contained in the air condenses and precipitates. The condensate can be collected and drained on the outside of the facade [32].

![Figure 68. Condensate trap](image)

This system is commented to be taken into account in future designs of building with the same kind of problem. It is a solution difficult to be implemented on the current window, but could be installed somehow taking advantage of the existent frames.

8.3. Selection of the best option

In order to select the best alternative of the above mentioned, the following criteria could be followed. Next to each criterion the considered importance of meeting it is shown.

- Cost (30%)
- Compatibility with the initial structure (30%)
- Obtaining best thermal conditions indoors (20%)
- Energy use (10%)
- Ease to install (5%)
- Material availability (5%)
For many of the solutions proposed the investment is unknown. Based on a personal opinion, the implementation of an electrically heated glass could be one of the best (if not the best) options. It would include at the same time the advantages of adding a radiator in the space and considering a secondary glazing or film. Indeed, as the heat is directly applied on the window, it would totally avoid the problem of condensation as the surface would be warmer. It is true that it entails some energy use, but only during winter, as the resistances could be disconnected during the summer.
9. DISCUSSION AND CONCLUSIONS

The energy analysis method used covers the study from an exhaustive point of view taking into account all possible heat losses and gains as well as searching the moisture sources which are the main cause to the problem.

Still, the work presents some weak points as could be the lack of measured data. In order to have an exact analysis of the staircase it would have been better to take some measures during the months when condensation can be seen on the window. Also, if inside temperature was known for every hour the study could have been developed more accurately and for more cases. The problem is that to obtain this temperature, it must be cleared up from a complex equation.

It must be highlighted that results are calculated for the particular conditions of year 2011 which was unusually slightly warmer than other years, making it possible for the results to suffer modifications when considering colder years. In any case, the results can be considered as valid for any general year.

As conclusion it can be said that, for the case of the current single pane window and all the different conditions studied, condensation takes place and that to establish a remedy, the dew point temperature has been determined in order to ensure that the indoor ambient temperature is kept above it for most of the time. The dew point temperature was found to be at 6.69°C, 4.26°C, 0.91°C, -0.55°C and -0.82°C for the months of October, November, December, January and February respectively. This can be appreciated in the following Figure.

Figure 69. Interior, Exterior, Surface and Dew Point temperatures
Thanks to the moisture transfer studied, it has been determined the humidity contribution of each source. This can be shown in the following chart.

**Figure 70. Moisture contributions**

It should also be mentioned that, as results show, the problems produced could have been avoided or at least reduced to a much shorter period of time if a 2-pane window had been installed from the beginning as it manages to increase the inside temperature by reducing the losses through the window in a 50.88%. In the following Figure it can be seen how for the case of a 2-pane window, the surface temperature is above the dew point temperature, avoiding saturation.

**Figure 71. Comparison between 1 and 2 pane window**

The work collects some interesting proposals to reduce the problems being caused with the minimum alteration of the current design outstanding between them the electrically heated window which by the installation of 73 panels of 80W each would be able to increase indoor temperature maintaining it above dew point for most part of time. This increase in temperature can be seen in the following chart.
Future investigations could be carried out analyzing every month of the year and for exact cases instead of using averages values. Further studies could also include the analysis of single large vertical windows orientated towards the South, and conclude if thanks to the higher heat gains, acceptable conditions would be reached. Also a continuation could be done studying the same balance in other locations and different years to obtain more general solutions.
REFERENCES


(http://www.gepvp.org/building.html)


[15] Infiltec: Large Building Air Leakage Test Calculator

[16] Hazim Awbi. *Basic concepts for natural ventilation of buildings.* Technologies for Sustainable Built Environments Centre University of Reading, UK


[21] Taghi Karimipanah. Humidity and the Indoor Environment,


### APPENDIX

**Appendix 1: Thermal resistances for surfaces and air spaces**

<table>
<thead>
<tr>
<th>Internal surface resistances</th>
<th>Heat flow direction</th>
<th>Thermal resistance $\text{m}^2 \text{K/W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td>Horizontal</td>
<td>0.13</td>
</tr>
<tr>
<td>Ceilings, roofs (flat and pitched) and floors</td>
<td>Upwards</td>
<td>0.10</td>
</tr>
<tr>
<td>Floors and ceilings</td>
<td>Downwards</td>
<td>0.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>External surface resistances (normal exposure)</th>
<th>Heat flow direction</th>
<th>Thermal resistance $\text{m}^2 \text{K/W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Roofs</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Exposed floors</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Unventilated airspace resistances</th>
<th>Heat flow direction</th>
<th>Thermal resistance $\text{m}^2 \text{K/W}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm (high emissivity)</td>
<td>All directions</td>
<td>0.10</td>
</tr>
<tr>
<td>5 mm (low emissivity)</td>
<td>All directions</td>
<td>0.17</td>
</tr>
<tr>
<td>25 mm or more (high emissivity)</td>
<td>Horizontal</td>
<td>0.18</td>
</tr>
<tr>
<td>25 mm or more (low emissivity)</td>
<td>Upwards</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Downwards</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>Upwards</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>Downwards</td>
<td>0.50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ventilated airspaces resistances (minimum 25 mm thickness)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Airspace in cavity wall construction</td>
<td>0.15</td>
</tr>
<tr>
<td>Airspace behind tiles on tile hung wall (includes resistance of the tile)</td>
<td>0.12</td>
</tr>
<tr>
<td>Loft space between flat ceiling and pitched roof lined with roofing felt or building paper</td>
<td>0.20</td>
</tr>
<tr>
<td>Airspace between tiles and roofing felt or building paper (includes resistance of the tiles)</td>
<td>0.12</td>
</tr>
</tbody>
</table>

**NOTE 1** More detailed data are contained in CIBSE Guide A5 [15].

**NOTE 2** In general, the surfaces of most building materials are of high emissivity. Low emissivity values are applicable to cavities adjacent to a reflective foil or foil.
Appendix 2: Saint-Gobain Glass datasheet for single pane window with Bioclean coating
**Appendix 3: U-value calculation**

**Exterior wall**

Concrete+Insulation+Concrete

\[
\text{R}_{\text{ext\ wall}} = \text{R}_{\text{out}} + \text{R}_{\text{concr}} + \text{R}_{\text{ins}} + \text{R}_{\text{concr}} + \text{R}_{\text{in}} = 0.04 + \frac{0.07}{1.7} + \frac{0.27}{0.035} + \frac{0.2}{1.7} + 0.13 = 8.04 \text{ m}^2\text{K/W}
\]

\[
\text{U-value} = 0.124 \text{ W/m}^2\text{K}
\]

**Interior wall**

Paint+Insulation+Foil+Insulation+Gypsum+Brick

\[
\text{R}_{\text{int\ wall}} = \text{R}_{\text{in}} + \text{R}_{\text{paint}} + \text{R}_{\text{ins}} + \text{R}_{\text{foil}} + \text{R}_{\text{gyp}} + \text{R}_{\text{brick}} + \text{R}_{\text{out}} = 0.13 + \frac{0.006}{0.04} + \frac{0.25}{0.035} + \frac{0.004}{0.033} + \frac{0.045}{0.035} + \frac{0.025}{0.17} + \frac{0.042}{0.6} + 0.13 = 9.17 \text{ m}^2\text{K/W}
\]

\[
\text{U-value} = 0.109 \text{ W/m}^2\text{K}
\]
Appendix 4: Saint-Gobain Glass datasheet for double pane window with Bioclean coating
Appendix 5: Saint-Gobain Glass datasheet for triple pane window with Bioclean coating
### Appendix 6: Solar Gard Ecolux (Saint Gobain) parameters

<table>
<thead>
<tr>
<th>Glass Type</th>
<th>Residential 14°C (mm)</th>
<th>Commercial 14°C (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single Pane Clear</td>
<td>Dual Pane Clear</td>
</tr>
<tr>
<td></td>
<td>Single Pane Clear</td>
<td>Dual Pane Clear</td>
</tr>
<tr>
<td>Visible Light Transmittance</td>
<td>33%</td>
<td>31%</td>
</tr>
<tr>
<td>Total Solar Energy Rejected</td>
<td>76%</td>
<td>76%</td>
</tr>
<tr>
<td>Solar Heat Gain Coefficient</td>
<td>.74</td>
<td>.74</td>
</tr>
<tr>
<td>Winter Median U-Value</td>
<td>.60</td>
<td>.59</td>
</tr>
<tr>
<td>Summer U-Value</td>
<td>.43</td>
<td>.42</td>
</tr>
<tr>
<td>Clare Reduction</td>
<td>63%</td>
<td>63%</td>
</tr>
<tr>
<td>Ultraviolet Rejected</td>
<td>99%</td>
<td>99%</td>
</tr>
<tr>
<td>Total Solar Transmittance</td>
<td>1.9%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Total Solar Reflectance</td>
<td>49%</td>
<td>49%</td>
</tr>
<tr>
<td>Total Solar Absorbance</td>
<td>3.4%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Visible Light Reflectance: Exterior</td>
<td>48%</td>
<td>46%</td>
</tr>
<tr>
<td>Visible Light Reflectance: Interior</td>
<td>30%</td>
<td>28%</td>
</tr>
<tr>
<td>Shading Coefficient</td>
<td>.28</td>
<td>.28</td>
</tr>
<tr>
<td>Emittance</td>
<td>.07</td>
<td>.07</td>
</tr>
<tr>
<td>Light to Solar Heat Gain Ratio</td>
<td>1.38</td>
<td>1.29</td>
</tr>
<tr>
<td>Solar Heat Reduction</td>
<td>7.2%</td>
<td>7.0%</td>
</tr>
</tbody>
</table>

All solar properties have been measured in accordance with NFRC standards. All values averaged from recently acquired quality control data.