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IN COLLABORATION WITH	CONTACT PERSON
SINTEF Community's in the context of NFR project called '*Healthy Energy-efficient Urban Home Ventilation*'.	Sverre B. Holøs

SUMMARY

This master thesis is a collaboration with one of SINTEF Community's project called *'Healthy Energy-efficient Urban Home Ventilation'*. The problems associated in the wet rooms is of high interest in the industry therefore the aim being to optimize the design and indoor climate, minimize the moisture-related problems and extend the service life of buildings. The main objective of this master thesis is to investigate how the various parameters affect the moisture levels and drying process after shower events in bathrooms. The parameters that are investigated include ventilation air flow rates, underfloor heating temperatures, slits under the door, temperatures for showering, flow rates of the water, lengths of the shower and locations of the ventilation valve. A total of 22 experiments were conducted over a period of 5 weeks in a bathroom module at SINTEF facility and each experiment was repeated twice. Considering the sequences before and after showering, prioritizing the atmospheric indoor climate and how it influences spatial air temperature and relative humidity. Primarily, Tinytag sensors were utilized for collecting data for air temperature and relative humidity; further to calculate moisture levels. The results showed non-uniformity in spatial air temperature and relative humidity with on/off underfloor heating. It was determined that the ventilation air flow rate had the most significant impact on drying time and moisture levels. In addition, an underfloor heating temperature change from 30 °C to 33 °C was less significant than a change in the slit under the door that yielded shorter drying time.

3 KEYWORDS
Moisture
Bathroom
Ventilation

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Oslo Metropolitan University,
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Abstract

Achieving comfortable indoor relative humidity and air temperature are desirable for any given user. As extreme levels of relative humidity can cause significant damages in buildings. Therefore, it of the utmost importance to navigate the moisture from the bathroom in an effective way thus reducing potential damage to the buildings.

The objective of the project at SINTEF Community that is linked to work package 3, is to find the optimal solutions and recommendations for ventilation strategies for urban residential buildings in Norway. Thus, in this study, certain parameters like ventilation air flow rate, underfloor heating temperature, slit under the door, temperature for showering, flow rate of the water, length of the shower and location of the ventilation valve were investigated. It was investigated how these various parameters will affect the moisture levels and drying time in the bathroom module at SINTEF facility. In addition, considering how spatial distribution of air temperature and relative humidity were affected under various parameters as mentioned.

Hence, a series of experiments were conducted at the SINTEF Community laboratory. A total of 22 experiments were conducted over a period of 5 weeks. Adjustments and modifications were made to the bathroom module by installing ventilation exhaust, underfloor heating, supply of water and drainage system. The choice of selected parameters was based on the literature review. In addition, a preliminary plan was devised to test and lock the parameters to limit the boundaries of the study and emphasises were laid upon parameters including ventilation air flow rate (36 m^3/h, 54 m^3/h, 72 m^3/h, and 108 m^3/h), underfloor heating temperature (off, 30 °C and 33 °C) and slit under the door (5 mm, 15 mm, and 30 mm). After conducting the preliminary plan, the length of the shower was locked at 10 minutes at 100% flow rate of shower water, 41 °C shower temperature and the location of the ventilation valve was above the shower area.

The results clearly yielded that the most significant parameter that determines the drying time is the ventilation air flow rate. Subsequently, combination of high ventilation air flow rate with slit under the door and underfloor heating turned on gives the most optimal results in this study. Concluding that the most effective way to control the moisture levels in the bathrooms is by increasing the ventilation air flow rate followed by underfloor heating turned on as this helps with rapid evaporation of water on the floor. However, when comparing an increase in underfloor heating from 30 °C to 33 °C is less significant than an increase in the slit under the door.

Sammendrag

Å oppnå komfortabel innendørs relativ fuktighet og lufttemperatur er ønskelig for enhver bruker. Ekstreme nivåer av relativ fuktighet kan forårsake betydelige skader i bygninger. Dermed det er viktig å navigere fukten fra badet på en effektiv måte og for å redusere potensielle skader på bygningene.

Hensikten til prosjektet ved SINTEF Communtiy som er knyttet til arbeidspakke 3, er å finne gunstige løsninger og anbefalinger for ventilasjonsstrategier for urbane boliger i Norge. I denne studiet ble derfor visse parametere som ventilasjonshastighet, gulvvarmetemperatur, avspalte under døren, temperatur for dusjing, strømningshastighet på vannet, lengde på dusjen og plassering av ventilasjonsventilen var satt i fokus. Det ble undersøkt hvordan disse ulike parameterne vil påvirke fuktnivået og tørketiden i baderomsmodulen ved SINTEF Hall. I tillegg med tanke på hvordan romlig fordeling av lufttemperatur og relativ fuktighet ble påvirket under ulike parametere som nevnt.

Det ble utført en rekke forsøk ved SINTEF laboratorium. Totalt ble det utført 22 eksperimenter over en periode på 5 uker. Det ble gjort justeringer og modifikasjoner på baderomsmodulen ved montering av ventilasjonsavtrekk, gulvvarme, tilførsel av vann og avløpssystem. Utvalgt av parameterne var basert på litteratur studiet, i tillegg ble det utarbeidet en foreløpig plan for å teste og låse parameterne for å begrense studiet. Parameterne som er i fokus er ventilasjonshastighet (36 m^3/h, 54 m^3/h, 72 m^3/h og 108 m^3/h), gulvvarmetemperatur (uten gulvvarme, 30 °C og 33 °C) og spalte under døren (5 mm, 15 mm og 30 mm). Etter å ha utført foreløpig plan ble det bestemt, lengden på dusjen ble låst på 10 minutter ved 100 % strømningshastighet av dusjvann og plasseringen av ventilasjonsventilen var over dusjområdet.

Resultatene viser tydelig at ventilasjonshastighet er den mest avgjørende parameter som er med å avgjøre hvor fort rommet tørker. Dermed kombinasjon av høy ventilasjonsluftmengde med avspalte under døren og gulvvarme på ga de mest optimale resultatene i denne studiet. Studiet konkluderte med at den mest effektive måten å kontrollere fuktighetsnivået på badet på er å øke ventilasjonshastighet etterfulgt av gulvvarme slått på siden dette gir det raskeste tørketid ved rask fordampning av vann på gulvet. Men når man sammenligner en økning i gulvvarme fra 30 °C til 33 °C er mindre signifikant enn en økning i avspalten under døren.

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Nomenclature, symbols, and abbreviations

Symbol/Abbreviations	Term	Unit
AH	Absolute humidity	g/m^3
ACH	Air change rate	h^{-1}
ρ	Density	kg/m^3
h	Enthalpy	kj/kg
HVAC	Heating, Ventilation, and Air Conditioning	-
Δv	Internal moisture excess	g/m^3
IAQ	Indoor Air Quality	-
m	Mass	kg
G	Moisture production	g/h
φ	Relative humidity	%
Mg	Molecular mass of a gas	kg/k·mol
P	Pressure	Pa
p_i	Partial pressure	Pa
p_c	Critical pressure	Pa
p_{tot}	Total air pressure	Pa
p_{sat}	Saturation pressure	Pa
p_v	Partial pressure of water vapour	Pa
p_a	Partial pressure of dry air	Pa
R	Universal molar gas	J/k·mol·K
θ	Temperature	K
λ	Thermal conductivity	W/m·K
R	Thermal resistance	$K \cdot m^2/W$
x_i	Specific humidity	kg/kg
c	Specific heat capacity	J/kg·K
S	Slit	mm
v_i	Moisture excess indoor	g/m^3
v_e	Moisture excess outdoor	g/m^3
$\dot{V}$	Volumetric flow rate	m^3/h
V	Volume	m^3
F	Underfloor heating	°C

1 Introduction

The recent pandemic crisis had restricted many people to work from home and this has increased the time spend in the houses. Working and training from home is a new habit that are on the increase after the pandemic. Prior to the pandemic the average percentage of time spend in residential buildings was roughly 60% [1]. However, as we can imagine this percentage has increased ever since the pandemic. Therefore, new challenges arise due to these new changes and hence more focus is emphasized upon health and securing good quality. Thus, it is becoming important to focus on the indoor environment in homes and offices such that there is no harm or negative health effects in the indoor environments that people are exposed to.

As high indoor humidity levels and air temperatures in the winter can cause moisture related problems like mould growth and damage the construction over time. While high ventilation rates can give in unwanted dry air during the winter season causing dry skin conditions for people and dryness of the eyes and respiratory infections [2]. In addition, aside from human health problems, dry air can also cause damage to the building in the form of shrinkage cracking and delamination of the materials [3]. As a result, improvements in air quality and control of relative humidity can potentially improve and lower the risks upon health when considering change in indoor climate [4].

Hence, to ensure good indoor air quality (IAQ) in buildings with being mindful of the consequences as described above then it is vital to control the excess moisture levels. To find the acceptable risk levels of condensation and microbial growth that will minimize the problems with regards to indoor air humidity levels. In addition, to provide adequate solutions for ventilation rates. As a result, in this described context it is important to gain sufficient knowledge of how moisture behaves in buildings that is exposed to high moisture levels.

1.1 Scope and Motivation

Every year, the insurance sector loses tens of billions of Norwegian crowns (NOK) owing to water damage caused by a variety of factors. According to water damage data, compensation payments for all water damage in the previous ten years have totalled 4 billion NOK [5] . Wet rooms are to blame for a lot of the injuries. The insurance companies who have huge expenditures linked with this have backed the demand for a wet room standard [6]. As a result, insurance firms have been a primary driving factor in bringing better construction practices to the new standard [7]. The building acts and regulations in Norway have a chapter dedicated towards guidance of indoor climate and health that focuses upon e.g. IAQ, ventilation and moisture prevention [8]. Despite the requirements and guidance from the authorities, the problems of moisture damage in bathrooms continues to be a concern.

Energy demands has been rising across the world as we enter the era of industry 4.0 with smart technologies [9]. Therefore, the construction industry accounts for a significant portion of global energy use. As a result, boosting building energy efficiency is critical. Considering the heating, ventilation, and air Conditioning (HVAC) systems that account for a major portion of a building's energy use. Ventilation is an important topic in HVAC since it is responsible for both delivering good IAQ and reducing usage of energy in buildings. Hence, understanding mechanical ventilation is crucial not only for promoting energy efficiency in building however also for creating a better indoor environment for inhabitants and reducing the risk of health problems as a result.

Calculations on energy use and moisture levels are required in the construction industry such that it can guarantee that a building is both sustainable and healthy. Therefore, in the initial period of design, simulations are used throughout the design process in order to ensure that various structural and system solutions to fulfil the design requirements. In addition, try to optimize design parameters and system alternative. Simulations can be further used to examine problems that arise during the operating phase, such as moisture damage and excess energy demand.

The quantity of water vapour in the air is referred to as air humidity [10]. It is important to understand how indoor air humidity levels vary with various influencing elements and how it affects persons, and their environment is needed to necessitate the study objectives. Moisture damage is a major factor that is responsible for up to 60% to 80% if the damages that occur in buildings; a percentage that accounts for 10% of the damages is as a result indoor air related moisture [11]. In severe circumstances, improper air treatment, high moisture generation, or a defect in the building can result in excessive indoor moisture. Therefore, examining the moisture impact and trying to understand how it occurs in the buildings overall can reduce the damages that take place. Moreover, to meet the global climate target set by the United Nations [12], then it's critical to investigate upon how we can decrease the impacts from moisture. Providing houses with longer service life and less need of rehabilitation. Potential harm can be averted if we investigate the indoor relative humidity and moisture levels [11].

Variations in the moisture content of indoor air have an impact upon living organisms and construction materials [13]. With regards to bacterial recurrence, mould growth, fungus, shrinkage of furniture when considering construction materials. In addition, impact upon human health such as dry skin, itchiness, discomfort [13] as well as high levels of moisture in a structure can cause respiratory problems like asthma [14]. Therefore, to detect and avoid the harms that are caused from various moisture levels thus it is important to understand the factors that influence the indoor climate.

There are several factors that affect the buildings regarding the interior environment, the usage of space heating, and the hygrothermal conditions [15]. These factors are indoor temperature, moisture levels in combination with temperature, impact of material breakdown rates, microbe development and relative humidity [16]. With the advent of strict building requirements therefore heat, air and moisture simulations are becoming an integral part of obtaining the low energy buildings [17]. Meanwhile, lower construction temperatures also pose a greater danger to moisture related issues. The occupancy level of a residential buildings is also very critical characteristic to understand in order to calculate internal heat gains, energy consumption, ventilation demand and IAQ [18].

With the diversification of bathroom apparatus, ever higher levels of insulation, high airtight dwellings, and the introduction of smart appliances that did not exist in the past [19]. Thus, the relative humidity and indoor environment of the bathroom has changed significantly in the recent period. The idea of bathing and aims of it has evolved in tandem with bathing activity [20]. The activity of bathing has increased with regards to showering almost daily. As there is a requirement for more pleasant and cleanliness of bathrooms therefore it is curial to consider the relative humidity and indoor climate while constructing for the bathrooms [19].

For the design of air conditioning around the bathroom area, research has been conducted regarding the required ventilation rates to prevent dew to occur and hindering mould [21]. In addition, heating to lower the temperature difference to control the indoor climate [22]. There are ventilation methods related to indoor comfort in the houses during showering and the moisture transfer process [20].

Therefore, in this master thesis the motive is to investigate the required ventilation rates necessary to provide adequate solutions and recommendations for bathrooms. This study will take into account the different variables in the bathroom, e.g., ventilation air flow rate, underfloor heating temperature, slit under the door, temperature for showering, and eventually how they impact the drying process over time. Considering the sequences before and after showering, prioritizing the atmospheric indoor climate and how it influences air temperature and relative humidity. The problems associated in the wet rooms is of high interest in the industry therefore the aim being to optimize the design and indoor climate, minimize the moisture-related problems and extend the service life of buildings.

1.2 Research questions

This master thesis is a collaboration with one of SINTEF Community's project called '*Healthy Energy-efficient Urban Home Ventilation'*. The purpose of the project is to find the optimal solutions and recommendations for ventilation strategies for Urban residential buildings in Norway. As the population of Norway is steadily increasing and the cities are becoming more denser thus the need for apartment houses in urban locations is proportionally increasing with demand [23]. Therefore, the indoor environment in urban apartments is of the utmost importance as they are sensitive to changes in heat and moisture causing difficulties related to health problems. Hence, achieving comfortable temperature in the airtight houses are essential for healthy indoor environments [24].

This master thesis is linked to work-package 3 at the SINTEF Community and one of the important goals for Work-package 3 is to develop ventilation recommendations for bathrooms in apartments buildings. Such recommendations should minimize the risk of moisture damage to internal surfaces, stored materials, and inside constructions (interstitial condensation).

The main objective of this master thesis is to investigate how the various parameters affect the moisture levels and drying process after shower events in bathrooms. For this purpose, a series of experiments have been performed at the laboratory facilities of SINTEF Community. In addition, different parameters, such as mechanical ventilation air flow rate, underfloor heating temperature, slit under door, water temperature for showering, water flow rate and location of ventilation have been employed in an extensive parametrical analysis.

Main research questions

- Which parameters among mechanical ventilation flow rate, under floor heating temperature, and slit under door is most determining for the drying process?
- What is typical drying time after shower events?
- How spatial distribution of air temperature and relative humidity in the bathroom is affected by the various parameters?

1.3 Thesis Structure

Below is provided an overview for the structure of this master thesis. It begins firstly with a theoretical section for laying the background for the concepts. Followed by a state of art literature review that was conducted in the autumn semester prior to writing the master thesis. Next, methodology, results, and discussions section, finishing with a conclusion with future recommendations and considerations.

Section 2 deals with the theoretical background that gives the foundation for the work presented later in the sections. It is a key section for understanding the concepts related to moisture. Concepts like the humid air and relative humidity, moisture transport and heat transport, followed by brief theoretical process of shower sequences that occur as well as focus on ventilation and regulations are presented.

Next, section 3 is the state of art, contains partially the literature review that was conducted in autumn of 2021 for understanding and finding the studies that were investigated regarding the subject in matter in a broader approach that was narrowed down for this master thesis. Various studies were provided from SINTEF along with the authors own methodology for finding the relevant studies in the different databases. This section served as a purpose to increase the knowledge of the topic and familiarize the writers with the topic of '*Healthy Energy-efficient Urban Home Ventilation'*. The section is divided into two parts, where the first part delves into four relevant studies that draw great inspiration and this master thesis adds further to the knowledge these studies recommended for the future. While the latter part focuses more on the critical parameters that will be investigated in this master thesis.

Then, section 4 presents the methodology and the plan regarding the experiments conducted in the test module at SINTEF laboratory. It opens with a brief constraints and assumptions that were necessary to make for this section. A methodology is presented in detail that can be easily replicated and perform if one desires. Along with the equipment specification and calibration that was necessary to conduct prior to any testing. The purpose is to familiarize the reader with the goal and execution regarding the experiments.

Section 5 consists of the results and are presented using figures that illustrate the moisture levels, air temperatures and relative humidity. The first part showcases the parameters that affect the drying processes while the second part depicts the air temperatures and relative humidity of 5 different sensors in the bathroom.

Thereafter, section 6 provides a thorough discussion for the results that were earlier presented, discussing, and comparing the parameters against each other to find the most significant parameter. In addition, depicting which combination of the experiments yields the shortest drying time. A table is presented in this section regarding the drying time for all the experiments. Finishing this section with uncertainty with measurements and challenges that were faced in this master thesis.

In section 7 a concise conclusion is presented to sum up the findings and the objective of the master thesis. Followed by section 8 shedding light upon recommendation for future works regarding improvements in the bathroom module, the energy perspective and moisture buffering experiment with towel.

Section 9 shows the complete references, listed in numbers. Lastly, section 10 presents appendix providing a detailed account of all the work in this master thesis including laboratory images, calibration, calculations for mass flow rate of shower water and circulation pump. The weekly experimental plan is also provided in this section along with all the figures for all the experiments that were conducted.

2 Theoretical background

2.1 Humid air

Humidity is the content of water vapor in the air. It is stated as grams of water per cubic meter (g/m^3) or most commonly as relative humidity. Humidity also plays a major role in the treatment of objects made of wood or other material that attracts moisture from the air. It can contract, expand, change shape, or crack up [25]

Humidity is of great importance for the well-being and well-being of animals, plants, and humans. It is also essential for environmental materials; for example, wooden products should have a consistent humidity level to avoid cracking. In the Nordic countries, the recommended indoor humidity in the winter is 30–45 percent since humidity below 45 percent inhibits the reproduction of allergic dust mites. Although for shorter periods, even lower humidity causes little pain for most healthy people. When its hot outside, wet air feels unpleasant because the body can't get rid of the heat through evaporation (sweat). A humidity of 50-70 percent will feel comfortable to most individuals [26].

In a private house, the usage humidity, or the quantity of water daily activities release to the environment, is estimated to be around (three - nine grams of water per meter of air). This implies that at 20 ° C, water vapor from humans, cooking, washing, and personal hygiene could increase humidity from around (40% around seven grams of water per m3) to over (60% around ten grams of water per m^3). This is usually sufficient to maintain air comfort, provided the temperature does not become too high [27].

Large resources are frequently employed in hot places on systems to remove moisture excess and cool the air (air conditioning). Due to the possibility of moisture damage, increased allergy risk, and humidifier fever, mechanical humidification is not usually advised for pure comfort reasons [26].

2.1.1 Ideal gas

An ideal gas is one in which all atom-to-atom or molecule-to-molecule collisions are entirely elastic and there are no intermolecular attractive forces. It may be seen as a collection of perfectly hard spheres that collide but do not interact in any other way. All the internal energy in such a gas is in the form of kinetic energy, and any change in internal energy causes a change in temperature. when examining an ideal gas, four variables are considered:

1. Pressure, the force the gas is exerting in the given volume and the quantity of particles that are hitting the surface.
2. Temperature, the amount of heat energy available to be transferred into kinetic energy of motion. The higher the temperature the faster the particles move and vice versa.
3. Volume.
4. Moles, the number particles that are present in the volume.

These variables depend on one formulating into laws. When the moles and temperature are kept the same, meaning the same number of particles moving at the same speed. Then compressing the volume will increase the pressure, thus the particles will move more rigorously. This means that pressure and volume are inversely proportional and vice versa. This is expressed in Boyle's law, where [$P_1 V_1 = P_2 V_2$], if we double one variable, we must cut the other one in half in order to keep this equation valid. Volume and temperature are also related if we have gas in a balloon and when we heat it up. The particles will move more quickly in order to keep pressure constant or hit the sides with the same frequency. The volume will have to expand, and this means that volume and temperature are directly proportional if one doubles the other must double, this is expressed in Charles's law $\left[\frac{V_1}{\theta_1} = \frac{V_2}{\theta_2}\right]$. The combined gas law is like a combination of Boyle's and Charles's law. Avogadro's law says that equal volumes of gas at the same temperature and pressure contain the same number of molecules specifically that one mole of ideal gas occupies 22.4 L at standard temperature and pressure, regardless of the identity of the gas. All the variables correlate in one equation called the ideal gas law. Three variables define an ideal gas, and these are Absolute pressure (P), Volume (V) and Absolute temperature (T) [28].

$$P_v = \frac{m}{M_g} RT \qquad \sum_i P_i = P_{tot} \qquad P_i \cdot V = \frac{m_i}{M_i} \cdot R \cdot T$$ *Equation 1*

Where,

- P_v is the partial gas pressure of water vapour (Pa)
- m is the mass of the gas (kg)
- M_g is the molecular mass ($kg \cdot kmol^{-1}$)

- T is the absolute temperature (K)
- R is the universal molar gas constant with the value of 8.31441 ($J \cdot kmol^{-1} \cdot K^{-1}$)
- P_i is the single individual pressure of a single gaseous compound (Pa)
- P_{tot} is the total pressure combined (Pa)
- V is the gas volume (m^3),

2.1.2 Relative Humidity

The relative humidity is every temperature and pressure defined as the ratio of the water vapour pressure to the saturation water vapour pressure at the gas temperature [29]:

$$\varphi = \frac{P_W}{P_{ws}} \cdot 100\% \qquad \textit{Equation 2}$$

The total pressure is not taken into account in the definition. The same concept applies above 100°C. However, because the saturation vapour pressure Pws is larger than 1013 hPa (typical ambient pressure), the relative humidity in an unpressurised system cannot reach 100%. The definition is also applicable below 0°C. Condensation will occur at a lower humidity than 100 percent relative humidity, hence 100 percent relative humidity is likewise impossible (when the vapour is saturated against ice).

2.1.3 Absolute humidity

Absolute humidity is defined as the mass of water vapour in a certain volume from temperature and relative humidity. The water vapour is a gas that behaves similarly to that of an ideal gas at normal atmospheric temperatures. Thus, applying the ideal gas equation as shown previously and following the Magnus-Tetens [30] formula to obtain the saturation vapour pressure P_{sat} as a function of temperature:

$$P_{sat} = 6.112 \cdot e^{\left(\frac{17.67 \cdot \theta}{\theta - 243.5}\right)} \qquad \textit{Equation 3}$$

Hence, P_{sat} is the pressure (Pa) when the relative humidity is 100% and therefore, multiplying the expression of P_{sat} above by the factor φ/100 and deriving the formula for absolute humidity (g/m^3) from the ideal gas as it only expresses 'n' in terms of the variable's temperature and

$$Absolute\ Humidity\ (AH) = \left[\frac{\left(6.112 \cdot \left(e^{\frac{17.67 \cdot \theta}{\theta + 243.5}}\right) \cdot \varphi \cdot 2.1674\right)}{(273.15 + \theta)}\right] \qquad \textit{Equation 4}$$

relative humidity. The volume is defined (1 m^3), and the gas constant R is known, thus pressure is calculated as a function of both factors, thus the equation for absolute humidity expressed in equation 4:

2.1.4 Moisture production

When the outside air is pulled into the building via the ventilation system, it heats up and expands in volume. The larger the air, the higher the volume expansion when heated up, accordingly to the ideal gas law. Due to the volume expansion, the water vapor pressure p_v remains same. Heating reduces the concentration of water vapor, however the change in volume is negligible in most practical scenarios. As a result, it's considered that heating air doesn't modify the water vapor concentration. The water vapor concentration in the indoor air with a particular moisture production G (kg/h) in a room under stationary conditions is expressed as the following using this simplification [28]:

$$v_i = v_e + \frac{G}{n \cdot V} = v_e + \Delta v \qquad \textit{Equation 5}$$

Where,

- v_i is the water content in air indoor (g/ m^3)
- v_e is the water content in air outdoor (g/m^3)
- G is the total moisture production (kg/h)
- n is the number of total air exchanges (h^{-1})
- V is the air volume (m^3)
- Δv is the moisture excess (g/m^3)

The air exchange number n represents the amount of fresh air delivered, $\dot{V}$ (m^3/h), in relation to the volume of the room, V (m^3), with $n = \dot{V} / V$. It is usual to mandate that the outdoor air supply equate to a minimum of 0.5 h^{-1} air exchanges per hour ($n = 0.5\ h^{-1}$) for dwellings. The water vapor concentration of air extracted from a residence is determined by the condition of the air you ventilate with (outside air), the air exchange (the amount of ventilation air provided to the room), the moisture sources in the relevant area, and the room volume, according to equation 5. The humidity level in the indoor air will fluctuate over time, eventually reaching an equilibrium moisture level with the surrounding air. The water vapour concentration in the air eventually thins out when wet air is exhausted and new air is supplied into the room. When

$$G' = \left(v_i - v_u \right) \cdot n \cdot V\, dt \qquad \textit{Equation 6}$$

excess moisture production from an indoor moisture source is initiated, the moisture will not generally be provided at a steady rate and will thus have a non-stationary relationship. The moisture production from an indoor moisture source can be described as a time-dependent size G' using equation 6.

If the right-hand side of the product above is greater than zero, than the current zone has a moisture-generating source. Meaning, if the absolute moisture content of the exhaust air (v_i) is larger than the absolute moisture content of the supply air (v_e), a given source of moisture will create the amount of moisture G '(g). A numerical approach can be used to determine the total moisture production G' from an indoor moisture source. According to equation above 6, the total moisture generated in each zone is equal to the sum of a final number of equal distance intervals from a starting point a (s) from where the moisture excess begins to increase until the end point at b (s) where the moisture excess eventually reaches zero again [28].

Based on the number of known points, the number of intervals between these two points (n) can be freely determined. The precision of the summation is determined by quantity intervals, with several intervals increasing the accuracy. The total moisture production (G) expressed in grams can be calculated by summing the provided equation above as a Riemann sum over the interval [a,b] with an evenly number of distributed rectangles (g) [28].

$$G = n \cdot V \sum_{i=1}^{n} \left(v_i - v_u \right)_{(i-1)} \cdot \Delta t \qquad \textit{Equation 7}$$

Whereas the time represents, $\Delta t = \frac{(b-a)}{n}$

2.2 Moisture in indoor environment

A good indoor climate in buildings is important for good health, well-being, and productivity. There are several physical parameters that affect the quality of the indoor climate such as the temperature of the air, comfort, the smell in the room and the lighting. The moisture content of the indoor air depends on [31]:

- Amount of water vapor in the air used to ventilate inside usually this is outdoor air.
- Internal moisture production and the possibility of moisture supply from other environments.

- The size of the air exchange e.g., the amount of ventilation air that is supplied and supplied away from the room as well as air leaks.

The moisture production indoors, the size of the air exchange, and the volume of the building are factors that contribute to the moisture supply in the indoor air in a building. The difference in water vapor content corresponds to the moisture supplement in a house. Poor ventilation and high moisture production are the most common reasons for the high values of the moisture supplement. In the event of air leaks in a residential building, the concentration of the water vapor content will increase and thus give a great risk of surface condensation and condensation inside the structure.

Moisture is present in all of the air that individuals come into contact with. The air contains water vapor under normal conditions, but it can also contain moisture in the liquid and solid forms of fog and frost, respectively. The quantity of moisture in the air, as well as the unit condition in which it occurs, varies with air pressure and temperature [32].

There is a limit to how much water vapor the air can hold at any temperature [32]. This maximum limit is known as the saturation content, and it reflects how much water vapor is present when the air is saturated with moisture. As the temperature rises, the air can contain more moisture, resulting in a reduction in relative humidity. When the temperature lowers, the air can store less moisture, causing relative humidity to rise. The temperature decreases to the point when the air's water vapor content equals the saturation content, which is when the dew point temperature is reached [33]. At this temperature the relative humidity is 100%. If the temperature drops further, the excess will off moisture precipitates. This excess can be precipitated as condensation on surfaces or as drops in the air. If it condenses on surfaces with a temperature lower than 0 ° C, it becomes condensation rhyme or ice.

Moisture, in one form or another, is responsible for a significant portion of the technical damage and issues that arise in a building. As a result, including moisture as a factor for assessing a building's functionality is critical. Moisture causes rot, microbial development, corrosion, frostbite, shrinking, swelling, among other issues (see figure 1 below) [34].

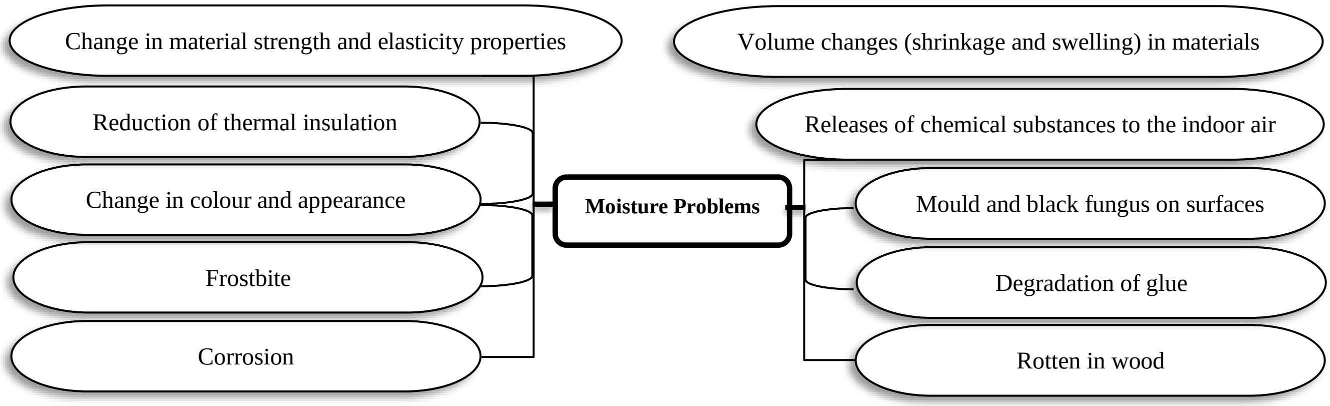


Figure 1: Moisture problems [66]

2.2.1 Moisture transport by vapour diffusion

The water molecules have great freedom in the vapor phase, they always tend towards an equalization of concentration in an enclosed space due to the great speed they have [34], this causes water molecules to penetrate a dry, porous material placed in moist air. This process is called diffusion. Of the various types of materials used in buildings, anything in contact with steam or water will absorb some moisture except for materials with sealed pores, such as glass and metals. In practice, moisture transport by convection is a much more frequent cause of condensation problems in the exterior structures than moisture transport by diffusion. Air tightness is also important to protect against moisture damage [34].

2.2.2 Moisture transport by convection

Natural convection can lead to the transport of large amounts of air and also of water vapor. Natural and forced convection are two types of convection. Condensation can occur when warm damp air is transported into a colder environment by natural convection. In the case of forced convection, the amount of moisture that may be transported through a material or component can be determined [34].

2.2.3 Moisture in materials

Moisture can bind to building materials in several ways. Moisture can be chemically bound in the material itself, but when the moisture content of a material is identified, reference is often made to the moisture in pores and voids that can be absorbed from or released to the environment [35]. Moisture can either be identified as absorbed air, moisture content, relative humidity in the air, or the pores of the material.

Materials that come into contact with moisture in vapor or liquid form will absorb more or less moisture. The exception is materials with a completely closed pore structure, such as glass and metals. The shape, size of the pores, and how they are distributed in the material have a great impact on the materials' moisture absorption and moisture transport properties. The calibres of the pores can vary from molecular size to several millimetres. Materials that can bind moisture in the pore system are called hygroscopic materials, wood is a hygroscopic material [36]. The moisture content of a hygroscopic material will be at constant temperature and moisture content gradually be adapted to the relative humidity in ambient air. Then the vapor pressure in the liquid layers in the material is as great as the vapor pressure of the room air. In this state, the material has reached its equilibrium moisture [36]. By measuring the equilibrium humidity at different relative humidity levels, too many materials have drawn so-called sorption curves that describe this moisture equilibrium. Wood and wood-based materials have unambiguously defined sorption curves where you can read the relative humidity that corresponds to the measured absolute moisture content or vice versa. When wood is moistened, it will adjust to a lower moisture level than when it dries out and this is called hysteresis [37].

2.2.4 Moisture buffering

Moisture buffering refers to the material’s capacity to control indoor humidity changes by absorbing and releasing water vapor [38]. The moisture content of the interior air might be passively adjusted by employing the qualities of hydroscopic materials of the building envelope and furnishing [39]. Moisture buffering flattens out changes in moisture levels, minimizing relative humidity peaks and achieving a more consistent indoor environment in terms of relative humidity. Moisture buffering works by causing hydroscopic materials to absorb (or desorb) part of the moisture in the surrounding air when the relative humidity changes, resulting in a reduced influence on the interior environment [40]. As a result, the change in relative humidity seems to be lesser than it may have been. Depending on whether the moisture content of a substance increases or decreases, the internal structure of the material regarding moisture is inhaled or exhaled through the pores. By taking use of this phenomena, active, energy-intensive methods such as dehumidifiers may be avoided, resulting in a more consistent moisture content in the indoor air, improved IAQ, and reduced energy consumption [38].

Relative humidity rises because of indoor moisture generation. The production's impact is mostly determined by the room's size and air change rate, but it may also be impacted by the furnishings and materials used. In two separate circumstances, researchers investigated how moisture generation affects relative humidity. One with moisture buffering from hygroscopic materials and one without. The internal air humidity was evaluated using a simulation of 1000 Swedish families based on obtained information and statistical data on climate, type of housing, resident behaviour, indoor moisture production rates, and technical characteristics [41].

2.2.5 Evaporation

The transformation of water from a liquid to a gas or vapor is known as evaporation. Evaporation is the most common mechanism for liquid water to return to the water cycle as atmospheric water vapor [42]. If the air in the room is not saturated, then there will be a concentration of water vapor present at the surfaces of the bathroom spreading further out into the room after a shower sequence. This concentration difference is the driving force of the mass transfer of water vapor to the air volume. The higher the temperature in the room and the lower the amount of water vapor it contains, the greater its ability to absorb water vapor. Subsequently the water droplets on the surfaces must evaporate before this process takes place. Evaporation as an endothermic process requires energy to detach the water molecules from each other, as well as release the surface tension [42].

The water droplets and the air are assumed to have the same temperature and therefore there will be no direct heat transfer between these. The energy must then be obtained from the latent heat of vaporization in the water, hfg, which is accompanied by a loss of tactile heat. This temperature drop is called evaporative cooling. When the temperature drops in the water, the saturation pressure also decreases, and this also gives a faster evaporation. There will now be a temperature difference between drops on the surfaces and the air in the room and heat transfer by convection begins. The heat loss in the water due to evaporative cooling corresponds to the amount of heat supplied by convection and can be expressed by equation 8 [43]:

$$Q_{conv} = m_v \cdot h_{fg} \qquad \textit{Equation 8}$$

Where,

- m_v is the evaporation rate
- h_{fg} is the latent heat of vaporization of the water at the surface

As a basic calculation for the evaporation of droplets on the floor and wall surface, it will be interesting to find the equation that applies to completely stagnant air. The stagnant air further contains a mole fraction of water vapor. In reality, there will be changes of air in the room with air velocity, that results in giving a faster mass transition. Thus, creating the opportunity to apply empirical correlations for mass transport. From a theoretical point of view the 1st law of thermodynamics can be implied here [42]:

$$Q + W = \Delta U \qquad \textit{Equation 9}$$

Where,

- Q = heat
- W = work
- U = internal energy, the total energy inside the given system

2.2.6 Heat transport

This thesis will address the temperatures in the air and on the surfaces as important parameters. Limited operating temperature will not be relevant, as dehydration usually takes place when there is no presence of wetness in the room. Henceforth, the radiant heat that is exchanged between the different components like walls, floor, and ceiling with varying temperatures on the surfaces.

2.2.7 Heat flow from the floor

The bottom of the test lab consists of concrete with a thin layer of tiles covering the entirety of the floor. The heating cables are counted as an energy generator, with a specific heat flux that propagates in the concrete. The temperature on the tiles floor will be a function of heat generation from the cables, heat conduction through concrete and tiles and finally the convective heat transport from the tiles surface out to ambient air. By assuming stationary conditions, a heat balance where all boundary layers have the same heat flow as shown in Equation 10 below. The heat flow through fixed materials in the floor are the same as the heat flow from the surface, where solid meets fluid, out to the air in the room.

$$Q\ \text{concrete} = Q\ \text{tiles} = Q\ \text{convective}$$

The solder line is considered as an imaginary y-axis and the heat flow from a heating cable connected via the path up to the surface and it is expressed using the Fourier's law [44]:

$Qy = ky \cdot A \cdot \delta T/\delta y$ *Equation 10*

Where,

- k is the thermal conductivity in the y-axis (W/mK) that is heat transferred in the area A (m^2)

2.3 Shower sequences – Theoretical process

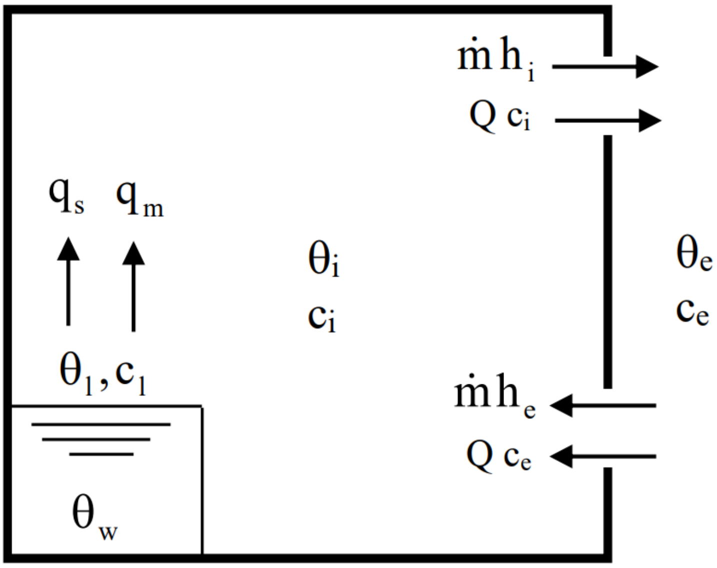
For the purpose of this master thesis, it was important to take into consideration the topic of interests that were going to be investigated later in the methodology section. Thus, terms like moisture and ventilation were essential to understand inside the test module.

In principle there are three concepts that are of the utmost interest and that includes the mass transport through air due to the exchange between moist and dry air. Secondly, the mass transport from free-flowing water on the surfaces through evaporation to the air volume and lastly, the mass transport of water vapour into the surfaces and materials in the bathroom [45].

When regarding the capillary suctions then the diffusive involvement of the moisture for the water will be the main factor on the surface [46]. The building sector in Norway has set recommendations for not building the bathrooms in connection with the external walls thus to minimize the potential risks involved to the structures [47]. If the interaction between water and exterior wall occurs, then at low outdoor temperatures will potentially increase the moisture transport significantly causing more damage. As well as the dew point will further penetrate the construction elements as the outdoor temperature becomes even colder. In result, two driving forces that increase the moisture content and if the moisture reaches the wind barrier, then ice can form freezing the elements and becomes denser. Hence, causing the transport of the moisture to slowly stop through the wall and excess accumulation will form, increasing the heat conductivity moving the dew point into wall by further exacerbating the problem. Therefore, bearing in mind this phenome one should construct the bathroom structure in such a way that they are protected from wetness and prevent moisture transport to damage the construction elements. Hence, mechanical ventilation should be unitized to control the excess moisture produced through various activities in the bathroom [48].

Transient phenomena of simultaneous heat and mass transfer from the liquid to the surrounding air occur given the assumed starting conditions for the water and air in terms of temperatures and moisture contents. An ascending mass flow rate of water vapour occurs, followed by a latent heat transfer, because the water vapour concentration in the bulk air is lower than that of the air layer next to the liquid, which may be considered saturated. On the other hand, sensible heat transfer mechanisms must be accounted for by assuming differing starting temperatures for the two domains — liquid and air. The interface liquid-air temperature is also expected to be the same as the liquid's bulk temperature meaning $\theta 1 \approx \theta w$ and that the ventilation process is the sole way for the system to exchange heat and mass with the outside. In terms of heat transfer, this entails assuming the same development of the bulk air temperature for the wall temperatures, i.e., that the process is adiabatic with regard to the impermeable boundary component of the system [49].

It is crucial to understand the process of drying in the wet room. Subsequently the process is divided into several stages starting with before shower, during shower, after shower (drying) and air dilution and reaching the flattening.



θi, θe - internal and external air temperature

θw - bulk temperature of the liquid

ci, ce - internal and external water vapour concentrations, respectively

θ1, c1 - temperature and saturation concentration on the interface liquid-air, respectively

qs, qm - sensible and latent heat transfer, respectively

ṁ, Q – mass and air flow rate

hi, he – specific enthalpy of internal and external air

Figure 2: The bathroom system [76]

2.3.1 Before shower

This is the equilibrium state where the vapour pressure is assumed to be at satisfactory levels. A slight air in the room that causes slow drying of porous materials on the surfaces. In addition, if the floor heating is active then the air temperature of the room will be higher than the air flowing in through the slit under the door. However, with the door completely closed and the air gap below the door will provide new air that will be an adhesive air along the floor, this effect is also known as the Coanda effect [50].

Thus, the heat transport in the air occurs as higher rates and the air will interchange will the atmosphere in the bathroom and outside the bathroom before reaching an equilibrium with the heated floor. Hence, as the bathroom further heats up the density of the air decreases and warm air will rise mixing with the air in the room as well as the incoming colder air under the slit of the bathroom door. In result the heating of the floor means that the bathroom will always have a higher indoor temperature than the other rooms meaning the relative humidity levels will be lower [51].

2.3.2 During shower

In this process, the visible water starts to settle as a water film and drips further on the surface. In regard to this master thesis, the quantitative calculation of the evaporation process will not be addressed but only during the dry process.

During the shower the water splashes because of the high flow rate of the water coming from the shower head and creates large droplets that become into smaller droplets as they further spread themselves over time. The kinetic energy in the event of a collision causes the surface tension that is incapable enough to hold the amount of water in large drops. Thus, the small droplets have the ratio of the surface area divided by the volume is therefore exposed to higher mass transport out to the droplets' water crust which is in contact with air. In contact with air, there will be a pressure gradient that draws on the water masses in the droplets, because the vapor pressure in the air just outside the droplets will seek equilibrium with the saturated pressure in the surface. This pressure gradient acts as a force on the evaporation and ceases first when the drop has evaporated, and equilibrium has been reached [52]. Only at relative humidity = 100% in the air closest surface, equilibrium can be achieved without full evaporation. An example of this is seen by cold pipes in rooms without much air changes [53].

If the water has a temperature of 41 °C, it is assumed that it will heat the wall to a certain °C and then when the evaporation starts, a process of evaporative cooling will lower the temperature in the water [54]. With large drops and with water film, the cooling will also be able to spread to the wall, floor, and air. On a typical wall, it will be possible to place drops of very varied size. In theory, they will hang on the wall, with a geometry that differs from a drop on the floor. A hanging drop is sack-shaped and is therefore assumed to have a greater exposure to air than a floor-lying drop. If the viscous forces that hold the water droplet to the wall are less than the weight of the drop, it will begin to flow. The dynamic friction represents one less force than the static, so that a drop that first begins to flow becomes difficult to stop and, in many cases, it will pick up more on the way and search for the floor. If the adhesion basis varies, the opposite can also happen if the drop loses mass on the road and becomes smaller, which reduces the mass and the weight gradually. When the weight becomes equal as the viscous forces stop the drop and linger again [55].

After evaporating over a period of time, then the ratio will be the surface area divided by the mass and this ratio will increase providing better conditions for adhesion and viscous forces. However, the conditions worsen over time due to gravity as the wall drops keep flowing over time and take time to evaporate. While the water is moving it provides heat transport to the air as the temperature of the water is high during showering. Then it emits heat in an efficient way and the conditions for the mass transport and heat coincide to a certain degree. Enthalpy transitions exist in all evaporation and condensation [55]. However, during the shower sequence, the provoked agitation of pulp and added heat through the shower waters above temperature will be dominant for the energy supply in the bathroom system.

2.3.3 After shower

The drying phase begins as soon as the shower sequence is over. As soon as the door is opened, some moisture will be released from the bathroom. The remaining moisture consists of the water vapor in the air and the water that has settled on the surfaces. There will be two parallel forces acting in different directions for the water vapor content of the air [51].

Firstly, the advective forces this means that there will be a continuous removal of water vapour when the supply air has a lower absolute humidity than the air ventilated out from the exhaust. Secondly, the diffuse forces that are the driving forces concerning the evaporations and while the water vapor concentration in air will seek natural equilibrium. Mass transport takes place from a place with a higher concentration of water vapor to a place with a lower concentration [56].

Air movements and temperature are quantities that will have a positive effect on mass transport from water to steam. Liquid water expands significantly at the transition to steam, so only small droplets will need a large volume of air to mix with before the water space is ventilated back to an equilibrium level with other rooms. If the air is completely or partially saturated, then it will take time for evaporation process initiates.

2.4 Ventilation

There are three types of main ventilation that are used to ventilate residential buildings. Namely, natural exhaust ventilation, mechanical exhaust ventilation or mechanically balanced ventilation [57]. The purpose of the ventilation systems in urban residential buildings is that it must secure satisfactory air quality for the users when it concerns health and comfort and in addition limit indoor humidity to hinder condensation and moisture damage for example mould growth. The energy requirements in TEK17 mean that in most cases you must choose balanced ventilation. Natural ventilation and mechanical exhaust ventilation deviate from the assumed energy measures in TEK17 but can be used if the ventilation heat losses are compensated with other passive measures, such as larger insulation thicknesses (Building Research Series 552.301).

The regulations now mention that one should only use balanced ventilation. However, in most Norwegian residential buildings there are only the previous ventilation variants. Balanced method gives you the right pressure in the different rooms in the residential buildings. In such systems, fresh air is supplied in a separate duct system to the living zones, and the fan for exhaust and supply air is located in a separate unit with heat recovery [58].

The main advantages of balanced ventilation are that you can recover the heat from the exhaust air and have a controlled, preheated, draft-free supply air supply. The disadvantage is more extensive canal facilities and higher investment costs. However, the overall economy will usually be good, somewhat depending on the efficiency of the heat recovery. In addition, there may be a risk of noise, but it may be reduced with noise traps and low-noise valves. Heat recovery is a key player when obtaining the right pressure in all rooms in the residential building, and the heat that is carried out of the house is recovered and used to heat the building.

Natural ventilation is a ventilation principle that relies on natural forces such as thermal buoyancy and wind pressure to drive ventilation. Natural driving forces can be used for one-sided ventilation, transverse ventilation, and buoyancy ventilation, among other basic strategies. In practice, a combination of these strategies is used to maximize each strategy's benefits [59].

In a room with only one outer wall open, one-sided ventilation is provided. Air flows through the opening due to a combination of buoyancy and wind forces. Wind forces can vary across the opening, causing it to pump. The buoyancy forces ensure that cold air flows into the lower part of the opening and hot air flows out of the upper part when the indoor temperature is higher than the outdoor temperature [59].

For the past 50 years, ventilation systems with mechanical driving forces have been the most common for municipal buildings and commercial buildings. In such facilities, smaller duct dimensions and more complicated ductwork can be afforded. This means that you often have to dimension the supply air and extract air fan to be able to provide more than 1000 Pa to ensure the necessary air volumes, which in turn results in higher electricity consumption, unwanted heating of supply air, and noise. The fan effect's share of the building's total energy consumption can be up to 15%. In recent times, low-pressure systems with low specific fan power have become more in demand. This reduces the problems mentioned but again requires a more integrated construction process. Where you actively go in to select duct guides, dimensions, and components with low-pressure losses [60].

The simplest form of mechanical ventilation system is an exhaust system. Here, the air is supplied directly from outside through slit valves, while an exhaust fan draws the used air out through ducts. In balanced mechanical ventilation, one has both supply air and an exhaust system. Fresh air is supplied here to the rooms after filtration and heating to a satisfactory supply air temperature. Capacity regulation of the plants takes place either by varying the temperature of the supply air, with a constant air volume, or by keeping the supply air temperature constant, while the air volume is varied [61].

Balanced ventilation uses approximately equal amounts of exhaust and supplies air to ventilate. Overpressure and under pressure are not used to control airflow; instead, fans are used. The heat is transferred to the supply air using heat recovery from the exhaust air in the unit. When the air supply is introduced into the unit, it absorbs heat from the exhaust air and distributes it via pipes to bedrooms and other living rooms. It also shows that the exhaust air is drawn from rooms where moisture is most likely to form, such as kitchens, bathrooms, laundry rooms, and storage rooms. Overflow between rooms with exhaust and rooms with supply air is required for the system to work properly, and this can be achieved by slipping above or below doors, indoor leaves, or valves between rooms [62].

The guide from Norwegian building authority states that the amount of ventilation must be designed based on the type of room, design, level of activity, pollution, and location of the ventilation. In addition, considering the moisture load from furnishing, appliances, materials, domestic pets and from humans. There is focus upon the quality of the air that the supplied air must be clean at a satisfactory quality before being supplied to the building, this is important as it prevents any health damages [8].

TEK 17 indicates an average value of fresh air supply in housing units at minimum 1.2 m^3 per hour and floor area. Minimum of 26 m^3 fresh air per hour per in bedrooms. Rooms that are not intended for permanent residence shall have ventilation that ensures 0.7 m^3 fresh air per hour per m^2 floor area. For housing units that are not inhabited or empty for an long periods of absence, then guidance in TEK17 states that the fresh air supply can be reduced [8]. According to Building Research Series 421.503 [63] it is recommended that there is a minimum of fresh air supply of 1.44 m^3 per hour per m^2 floor area when the living unit is inhabited to ensure good air quality.

The table 1 below shows the pre-accepted minimum exhaust volumes in the different rooms. The forced ventilation means that the amount of ventilation can be adjusted as required. A forced exhaust ventilation is good to prevent pollution air from spreading and smell. Therefore, it must be designed in an effective way in an optimal location.

Table 1: Recommended Airflow rates in houses from Norwegian building authority [90]

Room	Basic ventilation	Forced ventilation
Kitchen	36 m^3/h	108 m^3/h
Bathroom	54 m^3/h	108 m^3/h
Toilet	36 m^3/h	36 m^3/h
Washing room / drying room	36 m^3/h	72 m^3/h

Building regulations with guidance state three ways to calculate the ventilation need when the housing unit is inhabited. The largest amount of air is designed for the ventilation system's capacity during normal use. The ventilation system can be designed based on a minimum average fresh air supply in the dwelling, minimum fresh air supply per bed or at a minimum amount of exhaust air from the kitchen, bathroom, and toilet room at normal and forced exhaust mentioned in the Building Research Series 552.301 [64].

A ventilation system should have three capacity positions. Level 1 (low ventilation) can be used when the residential building is not inhabited, level 2 (normal ventilation) corresponds to air volumes during normal use and level 3 (forced ventilation) is used for forced exhaust from bathrooms or kitchens and is used for larger pollution levels in the indoor air. Forced exhaust can be switched on automatically when needed or controlled with a main switch. In most housing units, the minimum amount of exhaust air is desi for the ventilation need for normal and forced exhaust [64].

2.5 Regulations

Several national, international standards and guidelines state values for the parameters that matter for the thermal climate. Thermal Climate is among the parameters that are relatively simple and can be registered during an inspection of a problem in a building and most often can be easily adjusted. It seems satisfying thermal conditions are important for how people perceive the indoor climate including air quality [65].

Relative humidity is the ratio between the amount of water vapor in the air and the maximum amount of water vapor that the air may contain if the air was saturated and specified in %. Due to heating, the indoor relative humidity is often low in winter. Variations in humidity are well tolerated by humans. However, high humidity (>70%) can contribute to some unpleasant smells, mould, building damage, etc. Extremely low humidity (<20%) should be avoided due to problems with e.g., static electricity, mucosal and eye irritation as well dehydration of the skin. It is important to emphasize that it is not recommended to use humidifiers, this is because they cause a risk of pollution of the indoor climate [65].

Under normal conditions variations in the air humidity within 20-60 %, relative humidity has a little influence on how the indoor climate is experienced. In Sweden, the National Board of Health and Welfare has assessed the conditions as unfavourable concerning a hygienic judgment if relative humidity exceeds 45% through the day in the warming season [65].

Measurements of relative humidity can indicate whether the ventilation works well enough concerning the moisture load, as well as whether general moisture can be the cause mould growth and building damage by e.g., condensation of water vapor on colder surfaces. Experience of dry air is common in indoor climate problems. The feeling of dry air increases both with increasing temperature and with increasing air movement. One should be aware that probably the most common reason why indoor air is perceived as dry is elevated levels of irritants (particles, evaporation, and gases), more than the fact that the air is too dry. High temperature can also increase degassing from materials and thus increasing the irritating effect [65].

Air temperature is the most important measure of thermal comfort. Too high a temperature can give discomfort, fatigue, and impaired performance. The Laws or regulations don't contain regulated temperature limits. Recommended temperature requirements are specified in European standard EN ISO 7730 (established as Norwegian standard NS-EN ISO 7730) and NS-EN 15521: 2007. [65].

The embodiment of moisture into structures and other moisture-related incidents in the execution phase can at a later stage cause moisture damage with large financial losses and health problems for residents and users. The Norwegian standard NS 3514 is a guideline tool to avoid moisture-related incidents in the execution phase as well as increased awareness of moisture-proof construction. The standard contains requirements related to planning and implementation to prevent moisture (mainly precipitation) in the execution phase of a construction project from leading to damage to materials or structures [66].

The standard NS-EN ISO 13788: 2012 is for controlling the risk of condensation inside building structures. This standard describes internal moisture supplements based on five humidity classes, which also applies to buildings in Western Europe [67].

3 State of art – Literature review

The objective of this state of the art is to understand the extent and type of evidence in relation to '*Healthy Energy-efficient Urban Home Ventilation'*, considering the moisture excess, moisture buffering, moisture production and balanced mechanical ventilation impacts upon urban residential buildings. This section was in conjecture with the previous project work conducted in autumn of 2021 that served as a literature review. Helping the authors to adequately understand the previous research studies that have been conducted with regard to this master thesis.

The state of art presents various studies that included themes like moisture excess, ventilation and simulation tools that have been used in the industry. It gave an overview of what has been researched and experimented as well as the methods they have used. As this review demonstrates, this is a very complex topic that stretches several fields of study and can be approached from a variety of perspectives. Both numerically and experimentally, there are difficult methodological challenges here. This is also emphasized in many international works.

There are studies from different countries [14, 38, 39, 68-73] that have investigated field experiments in real buildings concerning indoor climate and moisture. Much of the work focuses on the phenomenon of moisture buffering in building materials and structures. Material moisture absorption varies and is affected by a combination of factors like ventilation, moisture production, and air temperature. In practice, the effect of moisture buffering cannot be predicted purely based on material properties, partly because it depends on the moisture resistance time course [70].

In the following sections the authors present four relevant studies before concluding with the significant parameters required for the methodology section. Delving into the detail of each study as it is important to understand the research made in the past to add and identity knowledge gaps for this master thesis. The four studies are the inspiration of this master thesis, and the authors took motivation from them to further improve and add to the methodology based on the study's improvements for the future section.

3.1 Moisture in bathrooms

In this subsection the authors will present four relevant studies that are important to set the bases for this master thesis. The four studies will especially focus upon the various parameters and the instruments utilized along with their placements in the bathroom. This will later be of aid in the methodology section for this study, as included in the preliminary plan for the design of the parametrical analysis.

3.1.1 Study 1, Norway

The first study [74] in focus was done by Anders Saasen Pedersen in 2018 at NTNU investigated the moisture production from indoor activities and influences it has on the relative humidity. The goal of the study was to verify a moisture production model that investigated urban apartment buildings, where the model was development by NTNU. Through several experiments that were performed in the living lab at NTNU that were tested for showering activities with different parameters. The parameters that were included in the study were the water temperature, flow rate of the water and the length of the shower to find the moisture production levels. In order to achieve a controlled volume, the tests were performed in a bathroom test model with a size of 5 m^2 such that the author could control the state of the air that enters and leaves the control volume. Meaning a mechanical extract valve was used for the air exchange and the door opening where the air could leave through. The material used in the bathroom was primarily tiles covering the floor and the walls.

Regarding the water temperature, the author had conducted their own research to find the optimal water temperature that users use averagely and set it to three different temperatures. Starting from 25 ℃, 35 ℃ and 45 ℃. Moreover, the flow rate of the rate was set to be operating at the capacity of 60% and 100%. Consequently, the length of the shower was set from the ranges of 7-minute, 5-minute, and 3-minutes as shown in the table 2 below, the author conducted in total eight tests.

In addition, to record and collect the data the author used different logger types like ‘Hioki LR8400-20’ a device that translates raw current voltage signals into real time readable data. Moreover, velocity sensor like ‘S+S Regeltechnik: KLGF 1’ to monitor the air from the bathroom that had inbuilt temperature sensors as well as sensors like Vaisala HMT120 to log the relative humidity and air temperature data in the bathroom. The author had placed sensors stationary for each trial in total of five sensors at different locations. Respectively, one at the valve in the supplied air, one under the door gap in the extracted air, one was measuring the total air pressure and lastly the final two were placed inside the bathroom at two different heights.

The experiments gave data ranging from 200 g/shower – 750 g/shower of the total moisture that was released during the trials. The author mentions that the transient development of relative humidity was similar to the moisture production model that he used at NTNU to simulate the conditions. The study showcased that there is apparent correlation between the parameters and the moisture production level because as the parameters were increased then the moisture production yielded higher values. In addition, it was mentioned that it takes roughly 40 minutes for relative humidity to reach a satisfactory level after the shower is turned off. However, it is suggested in reality the time is closer to 2.5 hours. This could be due to the transition from water vapour in the air that is quickly ventilated because of the evaporation of liquid water on the bathroom floor.

Table 2: Set of parameters, a total of eight tests [36]

	Water temperature 25 °C		**Water temperature 35 °C**		**Water temperature 45 °C**	
	Flow rate MAX	**Flow rate MED**	**Flow rate MAX**	**Flow rate MED**	**Flow rate MAX**	**Flor rate MED**
Time 7 min	-	-	-	-	-	*751g*
Time 5 min	*306g*	-	*481g*	*381g*	*656g*	-
Time 3 min	*244g*	*198g*	*303g*	-	-	-

Few of the recommendations the study mentioned in future considerations was that to conduct the showering experiment with greater range of the parameters like different ventilation rates and different recording points for the sensors. In addition, further improvements in the showering tests like replicating a more shower experience for example placing a beach ball for showering such that the splashes spread.

3.1.2 Study 2, Norway

Consequently, adding further from the previously mentioned study similarly another study [75] conducted on 2017 regarding the ventilation rates in the bathroom to devise a more accurate formulation of the Norwegian building code standards where the recommended value for the mechanical ventilation flowrate is 54 m^3/h in the bathroom and 108 m^3/h when showering. The study makes a claim that a constant ventilation rate at 72m^3/h is satisfactory for the transportation of moisture from the bathroom after a shower.

The experiments were conducted in a bathroom test module with the first parameter being the ventilation rates at mentioned above. Second parameter was the placement of the exhaust valves, having two different locations. Namely, one over the toilet and one over the shower. In addition, slit gap of 5mm for the door either above the door or under the door and underfloor heating ranging from 0 - 600 W that is considered comfortable temperature for the users that translate to 27 ℃ air temperature in the bathroom. The shower temperature was kept constant at 38 ℃ as well as the duration for each trial is kept constant at 30 minutes.

To measure the temperature and relative humidity the study used Extech RHT10 loggers, logging at each 30 second intervals and placed them in different stationary positions in the bathroom. Three were placed in the middle of the bathroom at different heights and one placed in the exhaust value while the last one was placed outside the bathroom door.

The study concluded with mentioning that 72 m^3/h is a better alternative because immediately after a typical shower sequence, the curve for specific humidity drops below forcing steeper than the corresponding curve at 54 m^3/h. applying to all cases, after that the forcing is turned off, the 72 m^3/h curve will catch up with the forcing curve and land on a lower moisture level in the long-term drying of the room. These findings apply to both the exhaust air and the air at the bottom of the wet zone. When forcing is cut, at a time when there are still capillary-absorbing surfaces that are still heavily moistened. Thus, based on this then it can also be added that a forcing of ventilation should also not be controlled by moisture in the air alone. Furthermore, the most optimal placement for the slit for below the door with a gap of 5 mm as the gap on top of the door gives sings of a short circuit of the ventilation air and would be insufficient. Lastly, the placement of the exhaust valve then this is the least critical parameter according to the study but does say that the exhaust over the shower is the better solution as this helps with removal of moisture buffering quicker than the other location.

3.1.3 Study 3, Japan

Furthermore, one study [76] that was published in Japan investigated the behaviour inside a bathroom and appurtenant changing room concerning amount of moisture produced. The experiment took place in different-sized bathrooms and changing rooms in a climate-controlled room. Plastic boards that do not absorb moisture, a space section, insulation, and composite material make up the walls of the unit-type bathroom. The changing room had an insulated roof and walls, as well as a wooden floor.

At three different locations, the vertical distribution of temperature and relative humidity in the upper and lower regions of the bathroom and changing room were measured. The relative humidity below the ceiling of both the bathroom and the changing room, as well as the temperature of the ceiling and each of the walls, were all measured. The air temperature and relative humidity in a vent in the bathroom doors were measured on the assumption that the temperature and relative humidity of the air entering and exiting the changing room were the same. In the exhaust duct attached to the ventilation fan, the temperature and relative humidity of the air exiting the bathroom were monitored. The windows were sealed during the experiment to reduce the amount of air going in and out via any holes other than the exhaust duct and bends in the doors. The ventilation rates that were used ranged from 65 – 130 m^3/h testing both the low and high ventilation scenarios. Below as depicted in the table 3 are presented the experiment scenarios with different parameters that were conducted in this study.

Table 3: The different parameters illustrated from the study 3 from Japan, showing the defined ventilation rates ranging from 65 to 130 m^3/h and various slit lengths [41]

Laboratory	Bathing style	Temp and humid of exterior	Ventilation during bathing	Length of opening a door [s]
T-1216	Showering	28℃75%	High, Low, Off	8
		20℃50%	High, Off	4
			Low	8
		10℃30%	High Low, Off	4 8
	Bathing in tub	28℃75%	High, Low, Off	8
		20℃50%	High, Off	4
			Low	8
		10℃30%	High, Off	4
			Low	8
Y-1616	Showering	20℃50%	High, Low	4, 8, 20, 40
			Off	8
	Bathing in tub		High, Low	4, 8, 20, 40
			Off	8

The quantity of moisture produced was obtained by calculating the moisture in the air and the moisture attached to the wall. The quantity of moisture adhering to the wall was wiped away using kitchen papers, and the weight change of the papers was used to calculate the amount of moisture. The amount of moisture in the air was determined based on how much moisture remained in the bathroom after ventilation. The quantity of moisture ejected by ventilation was determined using the amount of ventilation, as well as the air temperature and relative humidity at the supply and exhaust ports.

This study also mentioned that during bathing the relative humidity went beyond 100% immediately after opening the cover for the bathtub. This also caused increase in temperature in the changing rooms that were close to each other. They investigated the moisture in the surfaces and recorded their values. Suggesting that the moisture production during bathing was between 900 to 1300 g. The corresponding moisture that entered the changing room was between 20 to 50 g, although this was dependent on the time used to open and close the door, if the door was kept open then more moisture moved into the changing rooms.

3.1.4 Study 4, Sweden

A laboratory experiment was conducted by Jan Fransson [77] in a Swedish bathroom that was constantly ventilated by an exhaust fan. After a typical shower, measures of relative humidity, temperature, and local mean-age were taken. The majority of the measurements were taken in a non-heated environment. At a given air temperature, the maximum relative humidity in a bathroom is nearly constant. This does not appear to be the case with the under-the-bath measurement, where the maximum moisture content was determined to remain consistent.

The most precise measurements were taken just after the shower. Increasing the flow rate in the ventilation provided the best results. The greatest takeaway from the result the study mentioned was that the amount of vapour diffused throughout the room is reduced. The moisture content in the centre of the room and under the bath did not change as a result of the increased flow rate.

The experiment had used infrared heater that also led to a further decrease of moisture content in the centre of the room as well as moisture removal. The usage of a radiator only resulted in a decrease in the moisture content in the room's centre. Roughly 240 g of moisture is retrieved from the bathroom one hour after a shower, and approximately 340 g of moisture is extracted two hours after a shower. During the summer, when the moisture content in the supply air is high, the moisture extraction was substantially lower. Installing a dehumidifier to alleviate the moisture problem in the summer was said to be worthwhile since enhanced ventilation will only provide a tiny reduction. However, the disadvantage with this study was that it was done in 1991 and many advancements have been made since then, but it was beneficial to consider this study for the long-term comparison and development.

Furthermore, aside from conducting tests in the bathroom module at a test facility there were other studies [78, 79] that conducted field experiments, respectively at Oslomet and NMBU published in 2021. Measuring the temperature, relative humidity and CO2 levels in apartments buildings that had cross laminated timber (CLT) and balanced ventilation system with heat recovery. Both studies had taken measurements in bathrooms, bedrooms, kitchen and living rooms including the ventilation duct, calculating the absolute moisture content, and observing the fluctuations in the different rooms. The first study showed that the relative humidity levels measured were significantly low with mean values close to 25% for each room without the need for a humidifier. In addition, the mean moisture excess value was closer to 1.36 g/m^3 and they have conducted similar scenarios in WUFI plus that showed positive correlation that solidified their field finding. The latter study had relative humidity values ranging between 21.6-27.3% dependable of on the room and moisture excess was calculated to be close to 2 g/m^3 and the median value of moisture excess varies between 0.9-1.4 g/m^3.

To summarize the parameters mentioned above collected from the different studies, below is presented table 4 that shows all the parameters. These parameters will be taken into consideration when selecting the parameters for this master thesis later in the methodology section.

Table 4: Summarising the parameters from the four studies

Parameters							Sources
Shower length [min]	Water temperature [°C]	Flow rate [%]	Floor Heating [°C]	Slit [mm]	Ventilation rate [m^3/h]	Ventilation valve	
3, 5 & 7	25, 35 & 45	60 % & 100%	-	-	54	Over shower	[74]
30	38	100 %	26	5	54, 72 & 108	Over shower & toilet	[75]
10	20 - 28	100 %	-	4 - 40	65 - 130	Over shower	[76]

3.2 Critical parameters

Subsequently, to undertake the main research questions mentioned in section 1.2, it was important to study the previous literature that has been conducted with regards to the parameters the authors will use in the methodology section. Therefore, in this sub-section the authors will go through the parameters required to find out before conducting any experiments such that the authors could lock some of the parameters based on previous research and findings. This is an assumption the authors will have to make to limit the master thesis and narrow the scope of the research due to the time constraints the authors cannot not investigate each of the parameters.

3.2.1 Shower lengths

As shower length is a major parameter in the experiment that will be conducted therefore it is significant to find the average time spent during showering. Hence, from the different literature studies accumulated the authors found the most optimal shower length based on different articles, studies and assumptions from section 2 (state of the art) to replicate real world scenarios. When considering the shower length, this parameter has many variables that can influence the time of length used in the shower. For example, gender, age group, activity (sports) before shower, volume of hair on the head, habits, different shower height and routines. Listening to music and brushing teeth can increase the time of shower while in some regions where water is scarce then the shower length decreases. However, for this study's purpose the region being Norway that has abundance of water then the latter argument is negligible. In addition, the authors are assuming that the showering habits of the Norwegian inhabitants are of similar to the general European and American inhabitants.

One particular study in the UK by YouGov [80] surveyed over 2000 adults to find how long it takes the participants to shower. They discovered that for different sexes and age groups the number can vary however their results showed that women use on average just over 8 minutes while men averagely use just under 7 minutes. Surprisingly young adults below the age of 24 used staggeringly 10 minutes. Similarly, a report by an environment reporter published in BBC news by Mark Kinver [81] in 2011 revealed through data loggers that recorded over 2600 showers by 100 families in over a 10-day period showed that the average time spent by users in the bathroom is over 8 minutes where on average 9 litres of water is consumed during showering. In addition, study by Unilever and UK Water companies [82] found out that the average consumer spends just a little over 5 minutes and while 5% of the consumers spent just over 10 minutes. Furthermore, in Switzerland 11 litres per minutes is used while showering duration is 5 minutes at a temperature of 36 ℃ [83]. The water research foundation [84] conducted surveys in the United States that showed 5 litres per minute was used over a duration of 8 minutes of shower at an average temperature set at 40 ℃.

3.2.2 Water temperature and flow rate during shower

The temperature of the water during showering is also a significant parameter that will influence the relative humidity and temperature in the bathroom. Therefore, finding the average water temperature preferred by users is important for this study. Hence, previously mentioned that in the United States the preferred temperature is 40 ℃ while in Switzerland it was 36 ℃. Similarly, another study [85] found the preferred water temperature and flow rate during showering in Japan was between 40 and 44 ℃. In addition, another study [86] published in 2018 that investigated the household water temperature found that the temperature fluctuations lie between 38 to 42 ℃. This was the desired temperature for many of the users. However, the fluctuations occurred due to the seasonal changes and there was a strong correlation between using higher shower temperatures in the winter season and lower shower temperatures in the summer season. Furthermore, a dermatologist Sejal Shah from New York City recommends a temperature for showering between 38 °C and 41 °C [87].

To conclude since the season the experiments are going to be carried out are in winter then the temperature for this experiment is set to be at 41 ℃ based on the literature studies and an additional shower temperature at 35 ℃ to measure the changes between the two.

Fjordkraft that is the Norwegian power company in Norway wrote an article [88] based on their consumers usage and mentions that an average shower among their consumers is roughly 16 litres per minute and the users spent 10 minutes in the shower.

3.2.3 Underfloor heating and ventilation rate

Underfloor heating is popularly used in Norway thus it is important to consider this parameter and setup the underfloor heating in the test module. However, implementing and setting up the underfloor heating requires finding the average comfortable temperature the users in residential buildings find the most appropriate. Hence, a study in the journal of Energy and Buildings [89] mentioned that in order to have a comfortable room temperature in the bathroom then the floor heating needs to be set at 30 ℃ as this keeps the bathroom warm and dries the surface temperature, 30 ℃ of underfloor heating temperature retains room temperature of 27 ℃. In the standard of ISO 13732-2 [90] that is about human contact with surfaces at moderate temperature mentions that a room temperature of 27 ℃ is considered comfortable. However, to achieve and reach this temperature the water floor system needs minimum water supply of 30 ℃, but this depends on the type of materials and system used to heat up the underfloor as the high heat loss factor can increase the minimum required temperature of the water supply through the pipes.

Considering heating the underfloor then one article [91] mentioned that the floor covering of concrete floor will take between 2 to 8 hours to reach the desired temperature. While wooden and insulated floors require 30 to 60 minutes.

From the combination of the studies analysed above various ventilation rates have been used in the different studies. This is shown in the table 4 when presenting the four relevant studies.

3.2.4 Slit under door and ventilation valve location

The general requirements for moisture in the bathroom mentioned in the building technical regulations (TEK) says that ventilation of the slit under the door of the bathroom ensures rapid drying of the floor once it has been moistened [92]. The recommended slit opening under the door mentioned in the Building Research Design Guides [93] in 552.303 that slit opening of 15 mm is used for a flow rate with 54 m^3/h and 30 mm for 108 m^3/h. However, other construction companies mention using 5 mm slit under the bathroom door as well [94].

Regarding the ventilation valve location then this parameter will be kept the same with the relevant four studies mentioned above that have the location of the exhaust over the shower. One of the four relevant studies mentioned that the location of the ventilation valve is the least critical parameter therefore this master thesis will invest more time towards the most critical parameters, thus assuming that the location of the ventilation valve will be over shower.

4 Methodology

This section provides the quantitative method of collecting the data, showing the planning phase of the experiments upon how the experiments were executed with the equipment that was used to collect data in order to answer the main research questions presented previously. Firstly, assumptions and considerations together with the description of the bathroom module is presented with detailed information. Secondly, prior to conducting the experiments it was important to calibrate the equipment utilized to prepare for a logging system. A preliminary plan for the design of parametrical analysis was critical in this section as the study is built upon the premises that are presented here. Concluding with the experimental process showcasing the measuring points and the plan.

All the figures shown in this section are private archives captured by the authors using their own mobile phone cameras and sketches made by the authors to present in this section.

4.1 Constraints and assumptions

To narrow the field of inquiry to what is most relevant to the thesis, few assumptions had to be made. Therefore, the emphasis is drawn to the preconditions that have been taken for the further work. Calculations have been made with a view to fitting in with the relevant test module, therefore the following reservations will apply to both measurements and calculations. This master thesis has not taken into consideration the capillary suction that takes place in the materials used in the bathroom like tiles. This excludes the qualitative considerations regarding Visible water and airborne water vapor.

Moisture content in the air is studied in detail through calculations and measurement collected for comparisons that dealt mainly with relative humidity and temperature. The comfort level and microbiological consequences with regards to low and high moisture content are not taken into consideration.

Regarding the prefabricated test module then the testing and calculations are conducted with an ordinary and simple urban residential type of a bathroom in an apartment unit that contains no exterior walls, roofs, or windows with a floor size of 4.8 m^2. Consequently, the geometry and external surface dimension will be different in real apartment buildings compared to the test module. However, this does not mean that the conducted experiment is of no interest in bathrooms with different geometries and shower heads, but comparisons must be made accordingly with adjustments.

The geometry of the test lab is important with regards to logging values at different locations. Therefore, logging at different locations will help one to determine the feasibility of data points as the geometry within the bathroom can differ greatly. Furniture can hinder or cause undesired air flows than it is the case with the prefabricated modules. Moreover, the modern building utilized the outer façade for other rooms such as living rooms, bedrooms, and kitchens. Therefore, the bathroom is often built in the centre and not exposed to exterior walls. Thus, neglecting the temperature fluctuations at the wall surfaces. In addition, most modern apartment buildings do not have inbuilt windows for their bathrooms. But such was not the case for this bathroom test module. It had to be manually sealed to airtight the window gaps.

4.2 Test facility in SINTEF

The experiment is carried out in SINTEF indoor laboratory hall. The hall has connection options for adjustable exhaust, with ducts that carry exhaust air out of the building. The bathroom test module stands on wooden poles, 0.15 m above the floor. The underside of the test module floor faces open air in the hall. The building mass of the hall is 40 - 50 years, which means that the density in exterior constructions cannot be considered complete and that there will not be a significant negative pressure in the hall in relation to the atmospheric pressure on the outside.

Inside the SINTEF hall there is a sensor that logs the temperature throughout the year. The temperature in the hall is kept to an average heat of 21 °C during a year. There is a radiator placed on the westside of the hall to maintain the temperature constant. Thus, there are factors that can affect air and the temperature inside the hall. For example, there is a delivery door on the east side of the building where the goods are delivered through, and the sensor shows large temperature fluctuations when the door is opened for a few minutes. There are also other ongoing work and experiments in the lab that could influence the IAQ and temperature.

Figure 4: The bathroom module when it arrived at the SINTEF facility

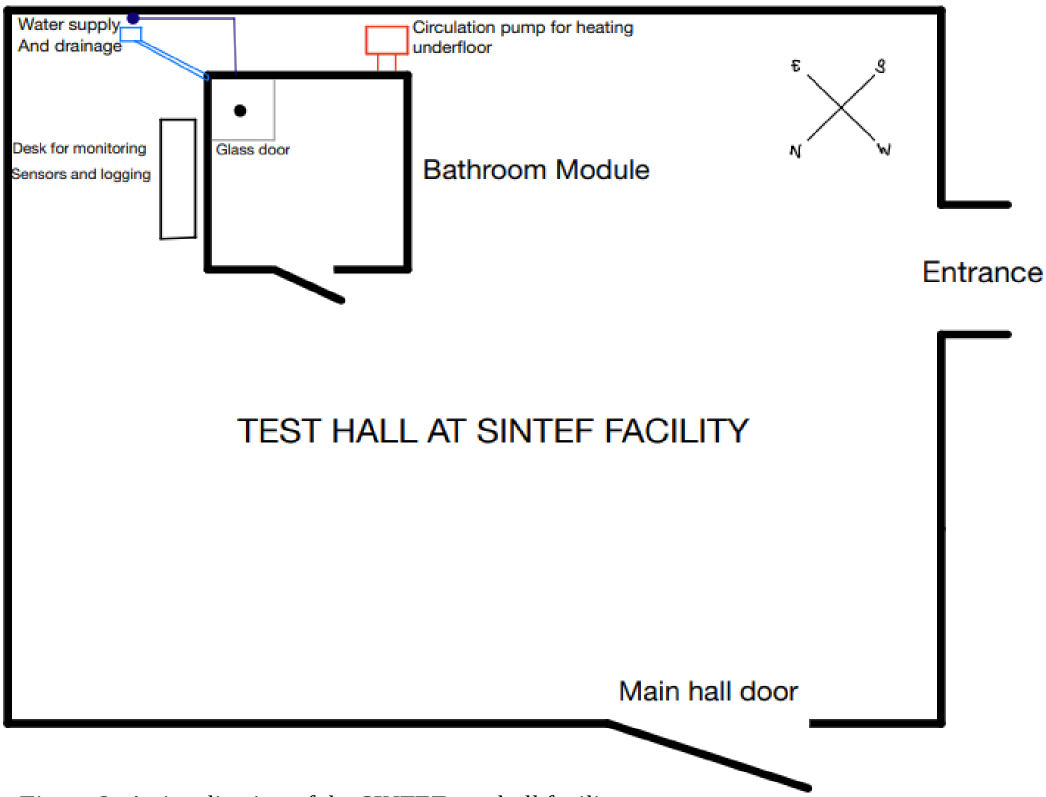


Figure 3: A visualization of the SINTEF test hall facility

4.3 Bathroom test module

The bathroom test module was provided by Probad for the experiment. Probad produces and delivers prefabricated bathrooms in steel fibre reinforced concrete with a focus on quality, functionality, and flexibility. The cabin was delivered with a zipper in the packaging in front of the door opening to make it easier to carry out inspections. The walls of the unit type bathroom are composed of concrete and the interior walls and floor had tiles that do not absorb moisture. The artificial test module was delivered to the SINTEF laboratory where the experiments were performed for SINTEF's project regarding called '*Healthy Energy-efficient Urban Home Ventilation'*.

The goal is to simulate a realistic bathroom that resembles a standard bathroom in Norway as the bathroom usage can vary and a model will enable to extend the results beyond the actual experiments. Thus, building upon the known physical affects along with simplifications and empirical verifications. Hence, achieving one of the goals of work package 3 at SINTEF that is to develop a ventilation recommendation for bathroom in apartment buildings.

The test module had exterior dimensions of 2.5x2.1x2.4 meters, where the dimensions of the door were 0.8x2.1 meter. The interior area of the bathroom was 4.8 m^2. Aside from the dimensions the bathroom had preinstalled toilet and sink with storage space beneath it. However, before starting on the desired experiments there were several things that required to be installed and adjusted in the bathroom that are explained in the next sub-section.

Figure 5: Outside view of the bathroom module before any work was done on it

4.3.1 Setups for the test module

In this sub-section a series of work that was done on the bathroom module is presented. This includes installing a door for the bathroom, connecting the water supply, setting up the drainage system, ventilation to exhaust air from the bathroom, circulation pump for underfloor heating to warm up the pipes, setting up glass doors for shower and doll’s head for splashing of water.

a. Door for the bathroom

A wooden door that can be opened and closed for easy access to the wet room module was assembled. The door was fitted with hinges, and extra wooden board was made with 15mm and 25mm to adjust the different slit openings for the experiment. In addition, attached gaskets around the framework of the door to completely seal and insulate the door when it is closed such that it is tight as possible during experiments.

Figure 6: Installing the door for the bathroom and attached gaskets for sealing

b. Water supply

One of the challenges was to get supply of water in the module and connect it to the drainage system. With the help from SINTEF's staff in arranging the practicalities of this, a water tap was installed with a mixer valve right outside the bathroom. Moreover, outdoor water hose was used to connect the water directly to the wet room module`s shower head. The shower head is mounted to the wall at the height of 1.65 meters from the floor. In addition, the mixer tap (placed outside the bathroom) from the water of supply had been marked with the desired temperatures of 35 and 41 ℃. To ensure correct temperatures, one Hioki wire was placed on the hose to confirm the right water temperature supply.

A thermostat was then attached on the surface of the mixer valve to measure the water temperature that is to be distributed to the bathroom. The desired water temperature for this experiment is discussed in the state-of-the-art section 2.

Figure 7: Mixer valve for adjusting the temperature for shower in the bathroom

c. Drainage system

The bathroom test module had a hole for the drainage to remove the water from the bathroom. However, it did not have pipes that could connect to the drainage. Therefore, a piping system was installed and connected to the drainage system. A drain that can operate normal amounts of water for a shower sequence was needed to remove water efficiently. A drainage pipe was placed under the test module, so that water goes through drainpipe after each sequence and the temperature of the water that goes out will be measured.

Figure 8: Drainage system, shower water returning from the bathroom

d. Ventilation exhaust

Installing a ventilation system to control the volume and the required piped for ventil system had to be assembled. The test module was delivered with six different exhaust holes and had different area diameters. For this experiment the hole location that is above the shower was used and the other holes on the roof were sealed with plastic foil and tape (figure 13). Furthermore, the exhaust over the shower (Ventilation valve) was connected to spiro ducts that was attached to the long exhaust pipe over the bathroom module resting on the roof then was further attached to the baas measuring station on the roof of test module. This was connected on to extractor fan to the outdoor air in the test facility (figure 9).

Different settings volume flow of the exhaust air was tested in this experiment. Airflow regulator duct is assembled in connection with a straight stretch spiro duct, this will help measure and control the profile for air velocity that goes out. Using a tool like TT 570 Micromanometer that assists with measuring and control the air that passes through spiro duct. This setup is illustrated in the figure 10 below with the dimensions.

Figure 9: Ventilation on the roof placed over the shower

Figure 10: Setup for the ventilation and roof of the bathroom, image on the left figure shows the parts that were used to later connect on the roof of the bathroom module while image on the right shows the roof of the bathroom module before any ventilation exhaust was deployed.

e. Underfloor heating

The thickness of the bathroom floor was measured at 0.1 m including the tiles. The bathroom test module came with integrated with underfloor heating. In this case, a heating cable was embedded in the concrete sole of a total of P = 120 W/m^2. Therefore, by connecting the circulation pipes with the preinstalled heating cables enabled the floor to heat up and creating a circulation of the heated water supply through the pumps (figure 11). Enabling to reach the desired average temperature that is considered comfortable by the users discussed in section 3.3.3.

Figure 11: Circulation pump for heating the underfloor, a heater that heats the water up to supply warm water for heating the floor of the bathroom

The figure 12 shows the infrared image taken by the camera showing the underfloor heating setup and the desired temperature, to showcase the placement of the cables. Neglect from the values shown in the figure as the purpose was to just illustrate the placement of the cables and heating area. Since the bathroom was placed 0.15 m lifted from the ground thus it was important to calculate the heat loss number for the bathroom module (shown in appendix G).

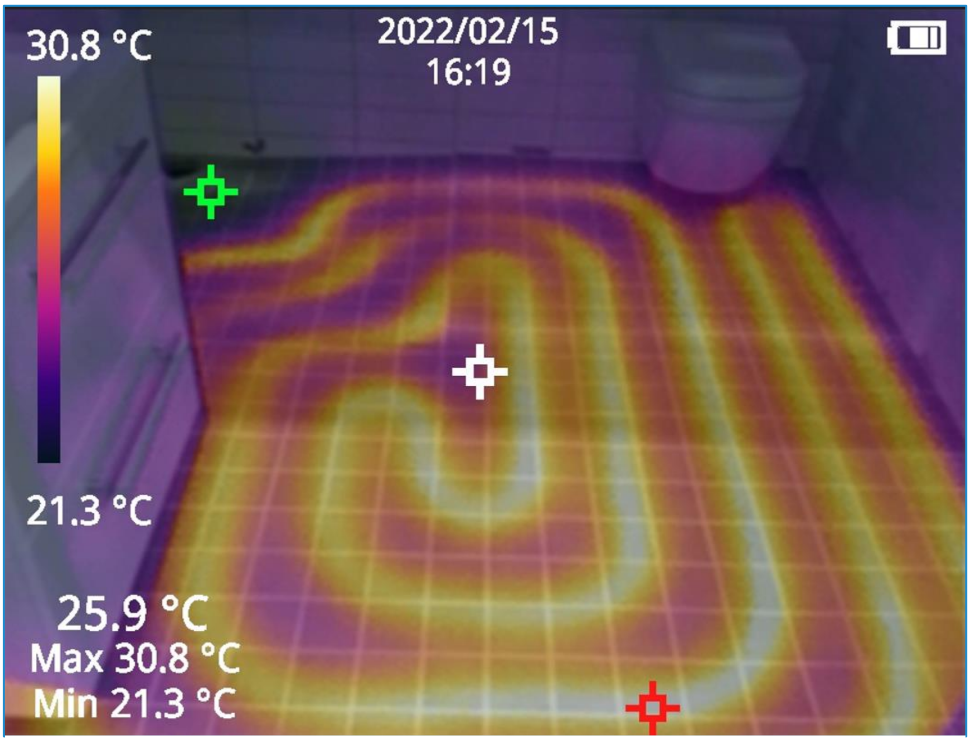


Figure 12: Infrared image showing the pipes under the floor of the bathroom, neglect the values as the purpose is to illustrate the piping

f. Doll head for splashing water and shower walls

In reality when taking a shower, the walls in the wet zone are significantly moistened with visible water, and much of this remains hanging on the wall even after a shower. To replicate a real shower scenario in this experiment a doll’s head was used to imitate splashes of water to the walls in the wet zone. The doll’s head was mounted to a stationary tripod that was placed in the shower zone. In this way, some of the water splashes out to the sides and hits the walls in the most realistic way possible. Entrance

In addition, glass doors for the shower wet zone needed to be assembled (figure 13). The glass doors (1.1x1.6m) covered the shower area and stopping the water from the shower to spread over the bathroom floor. The glass door acts like a shield and resembles a typical residential bathroom. The figure 13 below shows the setup for the doll's head wrapped in a plastic bag and the glass doors.

Figure 13: Showing the doll on the left image and the glass doors on the right image

4.4 Equipment specification

In order to achieve accurate results during experiments, the use of instruments to measure and monitor data was necessary. With the use of different sensor types, the amount- and state of the supplied and extracted air in the bathroom, as well as the total values of temperature (T), relative humidity, and the air pressure is monitored. All the various sensor types were placed in their same stationary place, during the different test trials in the room to log data. Table 5 below shows the different equipment used and what they measure during the experiment.

Table 5: Showing the equipment used in the experiment

No.	Product	Manufacturer	Type	Measures	Calibrated	Accuracy	Range
1	Tinytags	Gemini Data Loggers	ULTRA 2 TGU-4500	Relative humidity and temperature	18.01.2022	± 3%	32000 data
2	Heat flow logger	Hioki	LR8432-20	Temperature	07.02.2022	± 1.5%	Memory stick
3	Swema air 300	Swema	3000md	Ventilation	03.03.2022	-	-
4	Baas	Baas	-	Airflow	03.03.2022	-	-
5	Thermal Camera	InfiRay	-	Capture images	04.03.2022		14 GB
6	Micromanometer	Buckingham	TT 570	Airflow	03.03.2022	±2.05%	-
7	Omron sysdrive	Omron	3G3EV	Radiator	03.03.2022	-	-
8	CP11	Rotronic	-	Relative humidity, temperature, and CO2	04.03.2022	±2.05%	18000 data

Additional explanations of each product are discussed below.

4.4.1 Tinytags

To measure the relative humidity and the temperature of the bathroom, a device called Tinytags ULTRA 2 TGU-4500 was used. It had an inbuilt sensor that measures the relative humidity and temperature for indoor measurements. It has the ability to store up til 32 000 data. The instrumental measurement uncertainty for these devices is given to be relative humidity of ± 3%. In order to view the data a program called Tinytags Explorer is used along with the USB cable connected to the devices. Transferring the logger data from the device to the computer via the USB cable. The results show the time of measurement for each interval along with the

Figure 14: Tinytag Ultra 2 - TGU-4500 (left image) and Tinytag plus (right image)

temperature, relative humidity and dew measurements recorded during the experiment. In addition, Tinytags Ultra 2 – TGU-1500 was also used and has the same functions as the previous device mentioned but it had the ability to only log up to 7900 data and was waterproof.

4.4.2 Thermoelement

In addition, thermoelement called HIOKI LR8432 heat flow logger that uses a heat flow sensor to measure the movement and volume of heat energy was used to measure the temperature with a measurement accuracy of ±1.5%. Through recording multiple channels of voltage that are suitable for evaluating insulation performance and the temperature changes that occur while recording. When the data is recorded a USB drive is used to transfer the data to the computer from the sensor. The samples can record up to 10 milliseconds on every channel that is extremely accurate and rapid. It is an incredibly useful tool that shows the changes of temperature through real data and figures that make it much easier to keep track of fluctuations.

Figure 15: Thermoelement called Hioki LR8431 heat flow logger

4.4.3 Swema air 300

SwemaAir 300 is a micromanometer and recorder with anemometers for monitoring air velocity, volume, humidity, and temperature complying with ISO 7730 [95]. It is intended for precise ventilation system control testing and adjustment. The results of the measurements are presented on the instrument's display. SwemaAir 300 comes with several measurement programs and may be used with a variety of measuring funnels. SwemaFlow 125 is a cross-sectionally recognized measuring funnel. The air velocity is measured using wrapped heating wires above the cross section. The temperature decrease across the threads is an excellent indicator of typical air movement. SwemaAir 300, which is linked, calculates the air volumes [96]. Figure 16 displays an image of an anemometer and funnel.

Figure 16: Swema air 300 measuring the ventilation over the shower space

4.4.4 Baas measuring station

This product was adjusted to the duct dimension for ventilation valves and was mounted on the roof of the bathroom with a span of 1.7 m to ensure a fully developed speed profile through the measuring cross. Along with airflow templates that provide the measuring cross information about the volume flow through the channel. For this baas station measurement, it was manually adjusted as the values from the swema air 300 instrument showed deviations from the reference values to the real values (appendix K). After calibration it was shown that the correction value was significant.

Figure 17: Ventilation exhaust, image captured when conducting smoke test for illustration

Figure 18: Baas station

Figure 19: DP measurement

4.4.5 CP11

The CP11 is a portable measuring device that monitors and records relative humidity, CO2 levels, and temperature. In addition, determining the dew point and the temperature while wet. The device has a storage capacity of 18,000 CO2, humidity, and temperature readings. relative humidity has a measuring accuracy of ±2.05 percent. The device runs on batteries however comes with a charger that can be always plugged in during the measurement. The sensor is linked to a computer through a USB-cable, and the data is transferred using the ROTRONIC SW2.1 program. The data is saved to the computer as an Excel file as well as a created figure. In advance of the measurements, the date and time may be simply updated, as well as the time interval for logging [97].

Figure 20: CP11 Device

4.5 Calibrating the equipment

To decrease the uncertainty of measurements collected from the lab work. It was therefore important to quality check the equipment and remove any deviations on the measuring devices. Ensuring the calibration of the equipment will provide with more accurate data.

The purpose of calibration is to compare it with the measured value that is being measured against the instrument with greater accuracy. As measuring the instruments will give measurement errors due to rough surface, aging, corrosion and wear and tear. This can also impact the memory data that can have defects [98].

The data in each Tinytags had to be first erased using the Tinytags explorer software and had to be setup for 1-minute intervals and with an absolute relative start time. Meaning setting the start time of the devices at the same given start time. Therefore, the measurements will occur at the same time. A total of 6 Tinytags were initialized with this described setup. Next, to conduct the calibration an instrument called Rotronic was used, that is a HydroGen2 humidity and temperature generator. Thus, in the Rotronic device one can set the desired temperature and relative humidity values, in addition 6 Tinytags loggers were placed in the Rotronic instrument.

Consequently, the values that we set into the Rotronic were as shown in the table 5 below, bearing in the mind that the temperature and relative humidity expected to yield in the bathroom were chosen close to the values set in the Rotronic instrument. When there was a temperature change in the Rotronic instrument then the duration was set at 3 hours however a change in the relative humidity required only 1 hour duration. This was to make sure that enough time was given for temperature changes such that it would calibrate to the most accurate temperature and

Figure 21: Rotronic device with the TinyTags placed inside

relative humidity values.

Table 6: Calibration of the Tinytags in Rotronic

Date	Duration [hours]	Temperature [°C]	Relative humudity [%]
18.01.2022 12:00	3	10	40
18.01.2022 15:00	3	20	10
18.01.2022 18:00	1	20	20
18.01.2022 19:00	1	20	30
18.01.2022 20:00	1	20	40
18.01.2022 21:00	3	30	50
19.01.2022 00:00	1	30	60
19.01.2022 01:00	1	30	70
19.01.2022 02:00	1	30	80
19.01.2022 03:00	1	30	90
19.01.2022 04:00	3	40	20
19.01.2022 07:00	4	20	20

After conducting the calibration in the Rotronic instrument then the Tinytags sensors were connected to the computer via the USB and logged into the Tinytags explorer software to derive values for relative humidity and temperature. The deviations from the reference measurements were all calibrated and by exporting the log data into excel one could plot the 6 measured values for relative humidity and temperature against the referenced values and calculate a linear regression line describing the relationship between the two variables. Thus, it becomes easier to highlight any outliers that show significant deviations from the plotting of the data.

$$Y = a + bX \qquad \textit{Equation 11}$$

The field data was adjusted using the calculated displacement factors, where ‘a’ is the slope and ‘b’ being the intersection point, in advance of the data analysis. The regression line illustrates how the response variable ‘Y’ changes when the ‘X’ variable changes values as shown by the formula above. This is shown in appendix E.

4.6 Preliminary plan for design of parametrical analysis

The goal of the experiment was to examine a variety of common real-world circumstances on moisture production. The parameters were chosen based on prior literature research (discussed in subsection 3.2), as well as assumptions made by the authors in consultation with their supervisor. The moisture relationship may be investigated in numerous settings by adjusting a set of factors one at a time. Table 7 below shows the variables and parameters that are significant for investigation.

Table 7: The different parameters that were tested

Parameters	Unit	Variables			
Shower length	Minutes	5	10		-
Water temperature	°C	35	41		-
Ventilation rate	m^3/h	36	54	72	108
Slit [mm]	mm	5	15		30
underfloor Heating [°C]	°C	Off	30		33
Flow rate	m^3/h	Max (100%)			
Ventilation valve	-	Over shower			

Before starting on the main tests, a series of test runs were performed to check the quality of the bathroom and that the sensors were recording the data. The first week of the experiments would lay the foundation for the rest of the coming weeks. This means that in the first week of the experiment the authors locked the parameters like water temperature, shower length, flow rate and location of the ventilation valve. Thus, the remaining parameters like ventilation rate, slit under the door and floor heating were investigated. It was important to lock the parameters such that the authors can find the evaporation time and the effective ventilation rate inside the bathroom.

In most of the modern bathroom, they use underfloor heating and therefore a vital contributor towards increasing the evaporation rate of the visible water on the bathroom floor. Hence, setting the underfloor heating at a comfortable temperature based on presented previous studies. Regarding the selection of the parameter values then the shower length was set at 10 minutes and water temperature was selected at 41 ℃, as the basis for the experiments after the first week.

Measurements were carried out for determining the flow rate of the shower (see appendix F), where the time and the weight of the water was measured to determine the flow rate. This experiment was repeated six times to ensure a solid result for the flow rate. Thus, the value calculated came out to be 9,61 l/min at 100% flow rate. This value resembles well with the previous studies mentioned before. In addition, same experiment was conducted for the water circulation for underfloor heating and calculated a value of 8.33 l/min. However, human error should be taken into consideration such as reaction to stop the stopwatch, reaction to stopping the water tap running and the positioning of the pump had to be held at the same position each time for fair results. Moreover, water temperature was kept at 45 ℃ for each test such that the density of water is kept constant. One challenge was that to stop the water flow from the pump one had to manually take out the plug from the socket that required force and had to be in correlation with the time.

Furthermore, smoke test was performed inside the bathroom to detect any leakage that happens in the bathroom as well as observing the flow of air and the direction it forms inside. In addition, smoke test device was placed just outside the bathroom and pumped smoke under the slit opening to observe how the smoke behaves and after also placed inside the bathroom (appendix C). After conducting the smoke tests, it was concluded that the bathroom was tight and well-sealed.

To guarantee equal ventilation rate during experiments, then the airflow before each experiment was measured inside the bathroom exhaust using an anemometer (SwemaAir 300) and a funnel with a known cross-section (SwemaFlow 125). The air velocity is measured over this cross section by means of heating wires and any temperature drop over the wires gives a good indication of average air flow. This was important to control that the right ventilation rate is achieved and adjusted before any experiments were performed.

4.7 Experimental process

In total there were 20 measurements performed that were namely, recorded by 6 Tinytags loggers, 10 channels by Hioki, 1 CP11 sensor, 1 DP measurement for pressure and lastly one sensor in the hall for temperature and relative humidity. The Tinytags were the main source for analysis and the rest were placed for controlling the conditions within the bathroom. A total of approximately 7325 data points per experiment were acquired with the aforementioned measuring devices that logged temperature, relative humidity and dew point.

4.7.1 Measuring points

The measuring points were placed strategically to give a good representation of the air volume based on the four relevant previous studies mentioned in section 3.1. The measuring points were placed in the following positions starting with Hioki (1-10.), Tinytags (11-17.), CP11 (18.), DP (19.) and Hall sensor (20.):

1. Attached in the middle of the tripod that is in the middle of the bathroom.
2. Attached to the roof of the bathroom.
3. Attached to the floor of the bathroom.
4. Placed inside the shower head.
5. Placed under the door slit.
6. Placed inside the ventilation exhaust over the shower.
7. Attached in the bottom left corner of the shower.
8. Attached to the circulation pump for the supply water for underfloor heating (figure 10).
9. Attached to the pipe for the return water from shower (drainage, figure 7).
10. Attached to the circulation pump for the return water for underfloor heating (figure 10).
11. Attached in the middle of the tripod 1 m from floor that is placed in the middle of the bathroom.
12. Attached on the top of the tripod 0.1 m underneath the roof that is placed in the middle of the bathroom.
13. Attached on the bottom of the tripod 0.1 m from floor that is placed in the middle of the bathroom.

14. Attached 0.01 m above the shower head in the shower corner.
15. Attached under the door slit.
16. Attached outside the bathroom.
17. Attached on the shower glass door inside the bathroom.
18. Attached through a hole in the ventilation above the bathroom roof for CP11.
19. Baas measuring station (shown in figure 18).
20. Hall sensor (shown in figure 25).

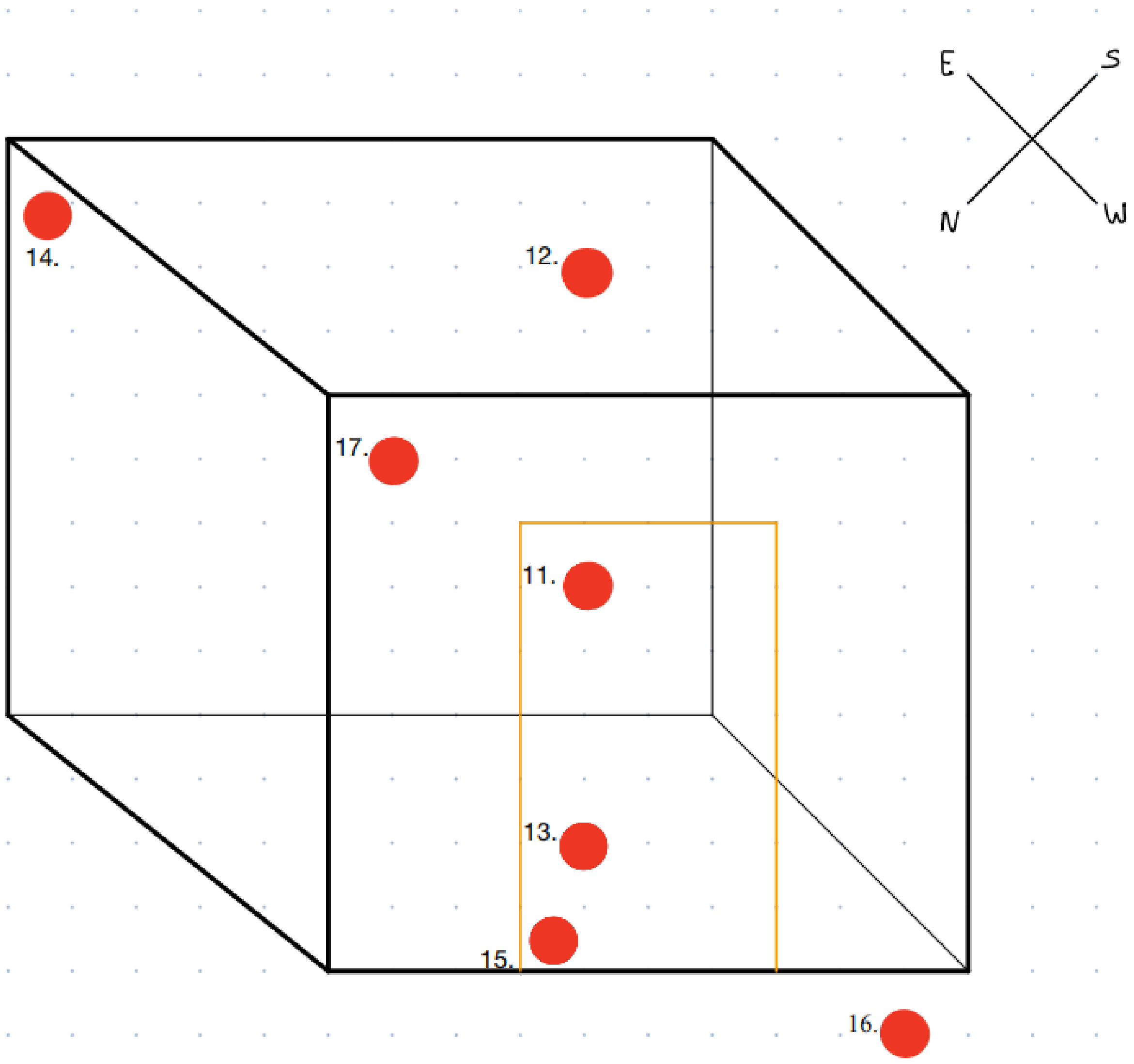


Figure 22: Showing the placement of the Tinytag sensors from position 11. to 17.

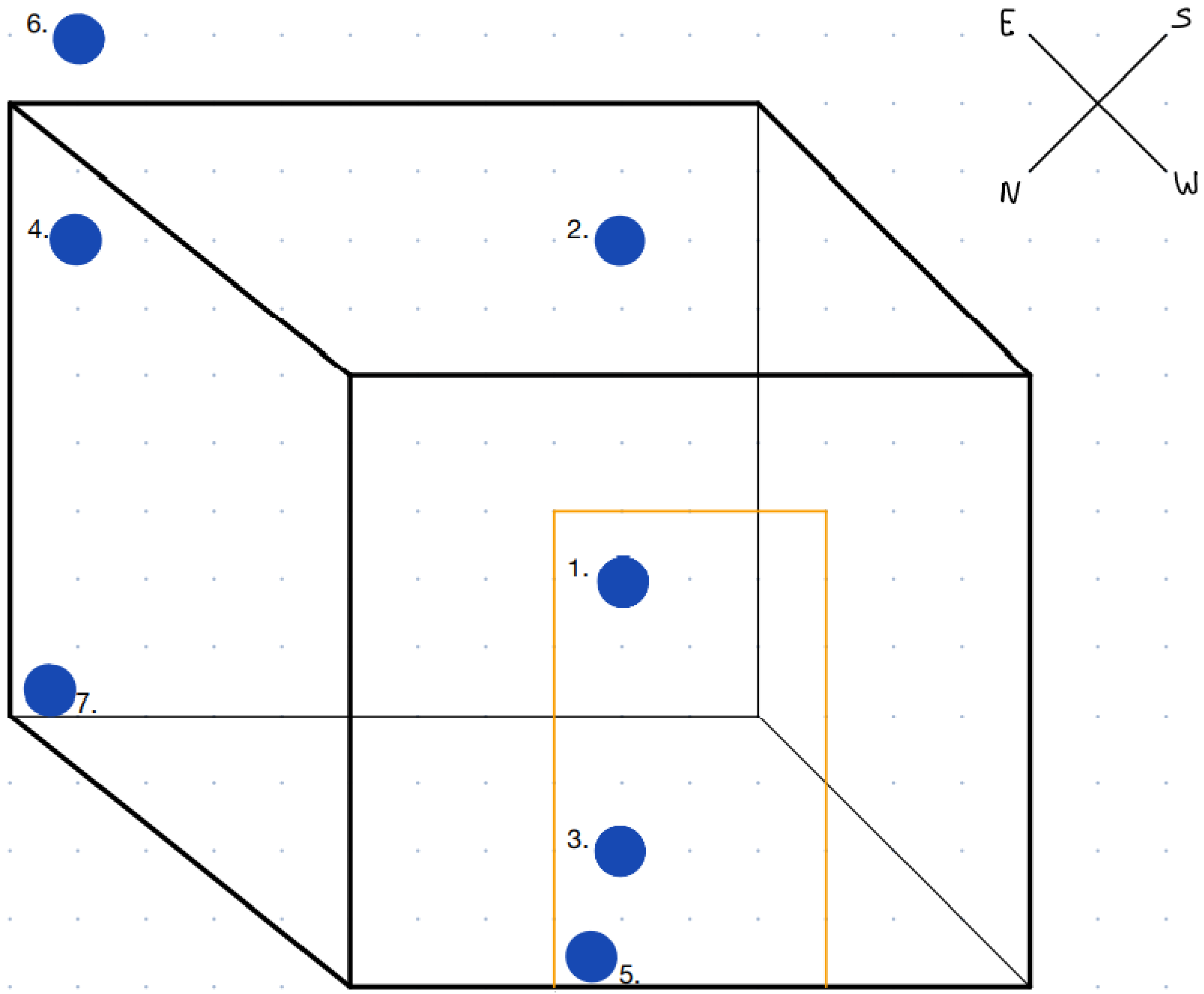


Figure 23: Showing the placement of Hioki sensors from positions 1. to 7.

Figure 27: CP11 sensor measuring point no. 18.

Figure 26: Hall sensor measuring point no. 20. Neglect the shown values.

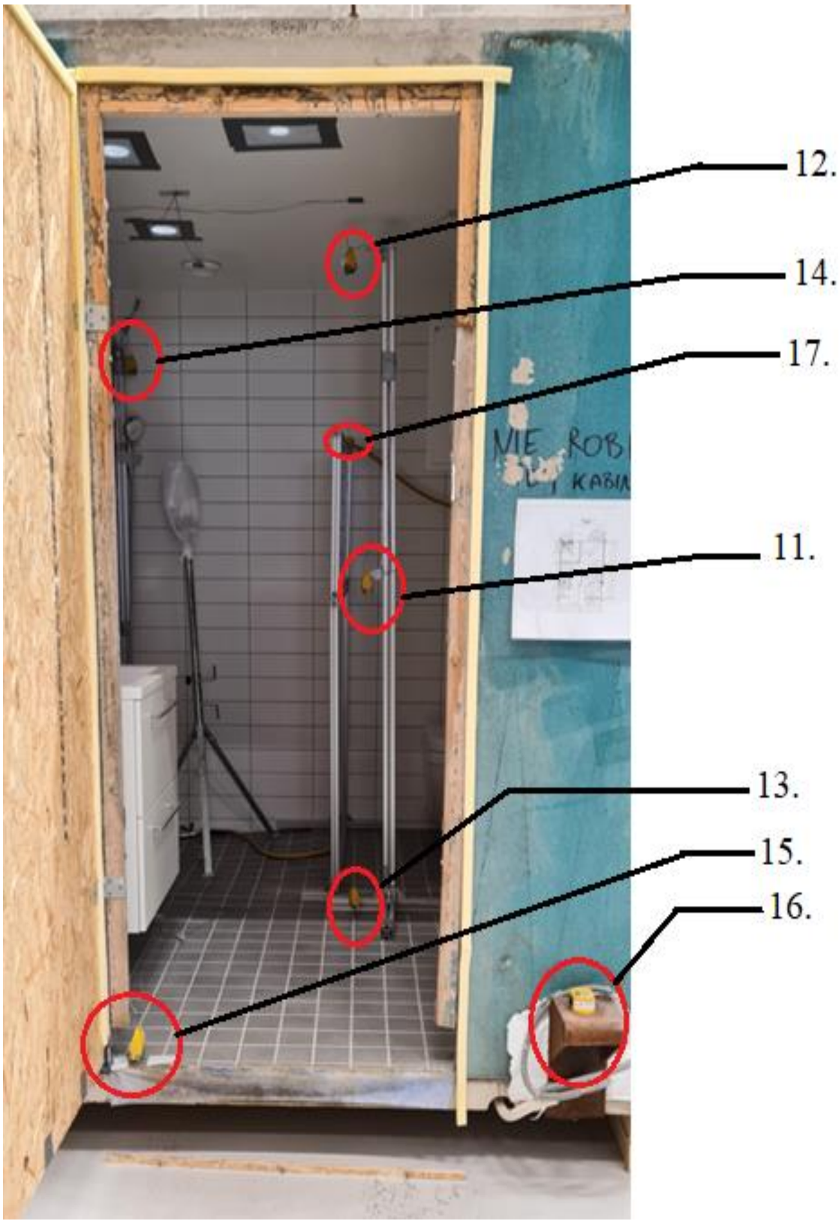


Figure 25: TinyTag sensors measuring point from no. 11. to 17.

Figure 24: The hall sensor is shown on the left, the hall door is shown in the middle and the backside of the bathroom module is shown on the right

4.7.2 Experimental plan

The experimental plan for the first week was designed to test the different variables such that one could control and quality check all the sensors such that reliable results could be presented to the reader. In addition, the purpose was also to find out the impact of the different parameters and which ones could be locked in after the first week of the experiments for the remaining period of the experiments. In total there were 22 experiments that were performed over a period of five weeks, each experiment was repeated twice on the same day. Thus, including the repeated experiments then it was in total 44 experiments that were conducted. In the first week, there were in total 10 experiments that were conducted, two on each day from Monday to Friday (table 8).

Table 8: Experiments performed for controlling and quality checking the setup

Series for each experiment										
Parameters	Monday		Tuesday		Wednesday		Thursday		Friday	
Shower length [min]	5	10	5	10	5	10	5	10	5	10
Water temperature [°C]	35	35	41	41	41	41	41	41	41	41
Airflow [m³/h]	54	54	54	54	36	36	54	54	36	36
Flow rate [%]	100	100	100	100	100	100	100	100	100	100
Slit under the door [mm]	15	15	15	15	15	15	5	5	5	5
Underfloor heating [°C]	Off	Off	Off	Off	Off	Off	Off	Off	Off	Off
Ventilation valve	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower

After conducting the experiments in first week it was decided with consultation with supervisors and based on previous research (section 3.3.) that the shower length will be locked to 10 minutes to replicate as realistic as possible model for showering and along with the water temperature at 41 ℃. The flow rate of the water and exhaust location were kept constant throughout the whole experiments as shown in the table 9 below.

Table 9: Constant variables that will not be changed throughout all weeks for the experiments conducted

Parameters	Units	Values
Shower length	m	10
Water temperature	°C	41
Flow rate	%	100
Ventilation valve	-	Over shower

Thus, for the rest of the duration of the experiments the parameters that were changed were the airflow rate, slit under the door length and underfloor heating. The table below shows the variables that were changed and set of series were performed with different combinations of the parameters shown below. The full experimental plan is shown in appendix H, week for week plan.

Table 10: The variables that will be changed throughout the experiments in all weeks

Parameters	Units	Variables			
Ventilation rate	m^3/h	36	54	72	108
Slit	mm	5	15		30
Underfloor heating	°C	Off	30		33

The raw data that was collected from the different sensors and extracted using a USB cable and were uploaded in a separate excel sheet for each experiment, keeping a structured order. Excel was extensively used to process the data for further calculations.

After transferring the raw data from all the sensors to a computer, then the moisture levels can be calculated based on the previously mentioned equation in section 2.1.3. with the measured air temperature and relative humidity for the entire experiment length. Then one can calculate the estimated moisture levels from an indoor moisture source.

5 Results

In this section the authors will present the results that were collected during the experiments performed in the bathroom at the SINTEF lab hall. The data from the experiments are shown in forms of 10 figures showing the development of the sequences and calculated the moisture level of each experiment series with air temperature and relative humidity.

The amount of moisture level released in the bathroom from showering and the way to deal with the moisture level is both dependable upon the various parameters. It is apparent from the conducted experiments that the most influencing parameters with regards to the amount of moisture release is from the shower water temperature, length of the shower, flow rate of the water and that is expected as if these parameters increase thus the amount of moisture will increase. However, parameters like ventilation flow rate, underfloor heating and slit under the door can hinder and help navigate the moisture levels in the bathroom to obtain the initial state of the bathroom air before the showering sequence had occurred. Hence, the latter mentioned parameters are of the utmost importance when determining the drying process hence for the results section these three mentioned parameters will be investigated. As the rest are explained to be remained constant throughout the experiments (section 4.7.2). However, what is intriguing for this master thesis is to find the most optimal combination for the parameters such that one combination that yields the most satisfactory levels for the drying process.

5.1 Parameters that affect the drying process

Recalling the previous literature studies then the placement of the sensors was based accordingly upon them. Especially the Tinytag sensors that measured the relative humidity and the air temperature at specified measuring points were used to determine the development regarding the moisture levels. The main Tinytag sensor that is presented in this section is the top roof tripod sensor (position 12.) placed in the middle of the bathroom module. The reason that this particular sensor is selected is because it is influenced by all the three parameters in focus, namely, the ventilation air flow rate, slit under the door and underfloor heating. Due to the placement of the sensor, it is in an optimal position as the distance from ventilation location is approximately the same in contrast to the distance from the slit under the door to the sensor. Thus, this sensor was considered to monitor the state of the air and how it was influenced by the shower sequences.

The figures below in this section showcase the drying time for all experiments. The drying time in this study is defined as the time it required for the bathroom module to obtain the initial state of conditions before the shower event started. Subsequently, the drying time would be from the time it took to reach the same moisture levels that were present in the bathroom before the shower event started. Thus, the results below are organized after increasingly ventilation air flow rate where slit under the door and underfloor heating changes from figure to figure.

The figure 28 below shows all the experiments that were conducted with slit 5 mm and underfloor heating turned off. It can be derived from the figure 28 below that the experiment with ventilation air flow rate 108 m^3/h yields the best performance regarding the drying process in the long run. However, ventilation air flow rate 72 m^3/h is slightly quicker in drying process in the first 15 minutes after the shower event has ended and is overtaken by the former mentioned experiment. The opening 5 minutes after the shower event has ended show closely similar rate of drying, the drop in the moisture level is approximately the same for the first 5 minutes. After this point the behaviour inside the bathroom changes and each experiment takes on its own path as it separates from each other.

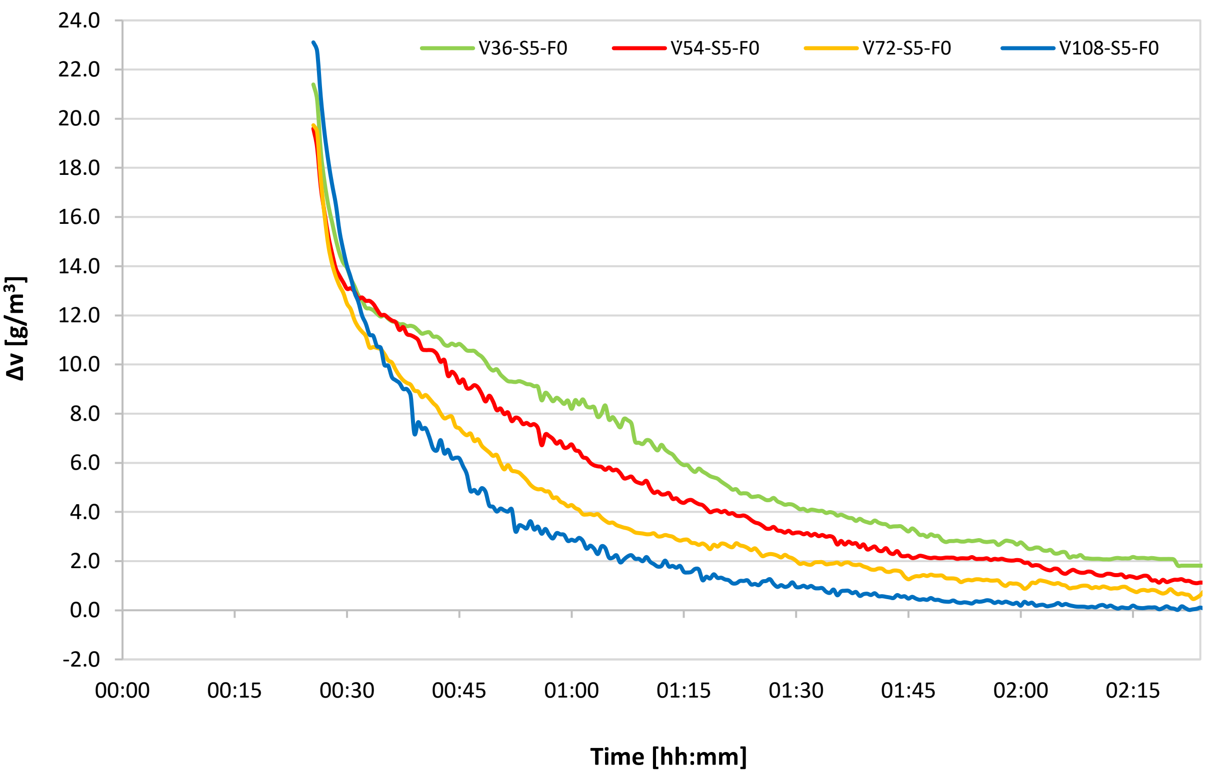


Figure 28: Moisture level near the roof monitoring position 12. at ventilation rates of 36 m³/h, 54 m³/h, 72 m³/h, and 108 m³/h with constant slit (5mm) and underfloor heating (off).

Similarly, the pattern continues as the figure 29 below shows the experiments with slit 15 mm and underfloor heating turned off. It is illustrated that the ventilation air flow rate with 72 m^3/h and 108 m^3/h are exceedingly quicker in the drying process while compared with the lower ventilation air flow rates. Again, the first 2-5 minutes appear to be the same in the rate of drying as moisture levels drop jointly with all the experiments until after 5 minutes have surpassed then the curves start to show differences. Insignificant difference between ventilation air flow rates 108 m^3/h and 72 m^3/h. This shows that increasing the slit to 15 mm while compared to the previous figure 28 has significant impact towards equalling out the drying process.

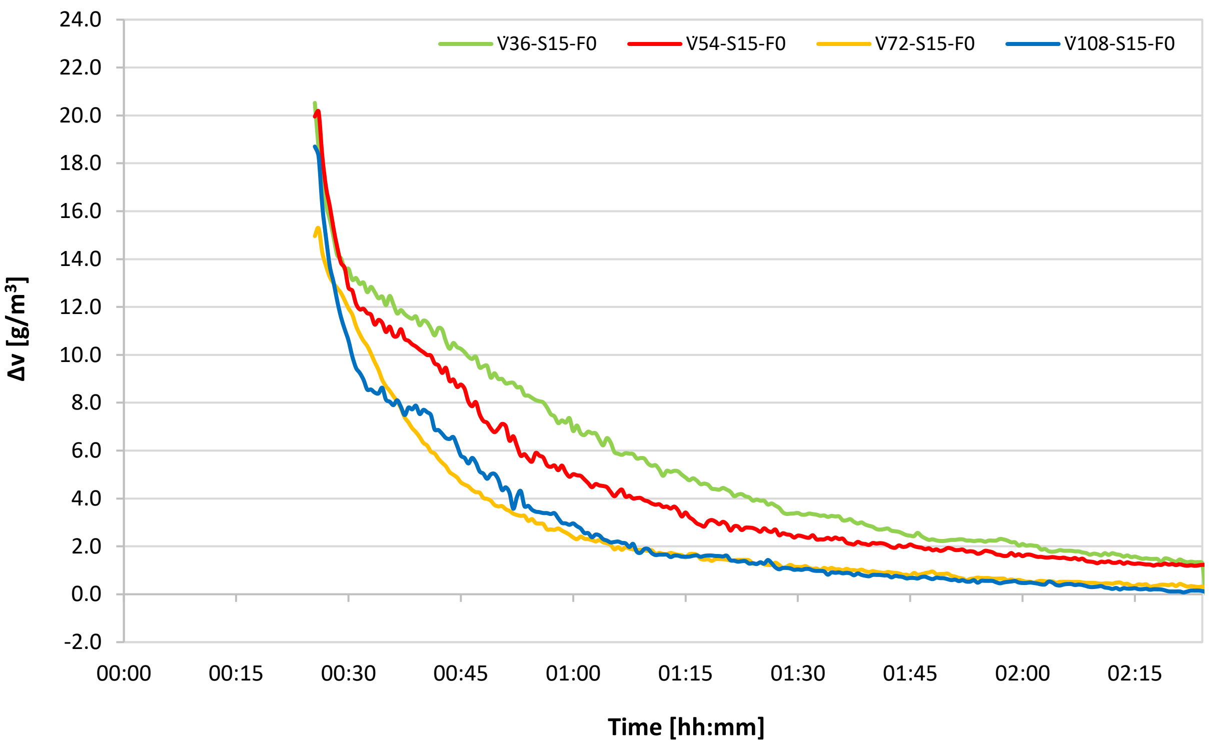


Figure 29: Moisture level near the roof monitoring position 12. at ventilation rates of 36 m³/h, 54 m³/h, 72 m³/h, and 108 m³/h with constant slit (15mm) and underfloor heating (off).

Moreover, the provided figure 30 below shows the experiments with slit 5 mm and underfloor heating turned on at 30 °C. A trend that can be observed is a shift downwards in the level of moisture in the figure 30 as compared to the previous figures above namely, figure 28 and figure 29. Similarly, the ventilation air flow rates with 54 m^3/h, 72 m^3/h and 108 m^3/h have very closer drying process as the curves start to even out after approximately 95 minutes have surpassed. However, the lowest ventilation air flow rate 36 m^3/h showed the slowest drying time.

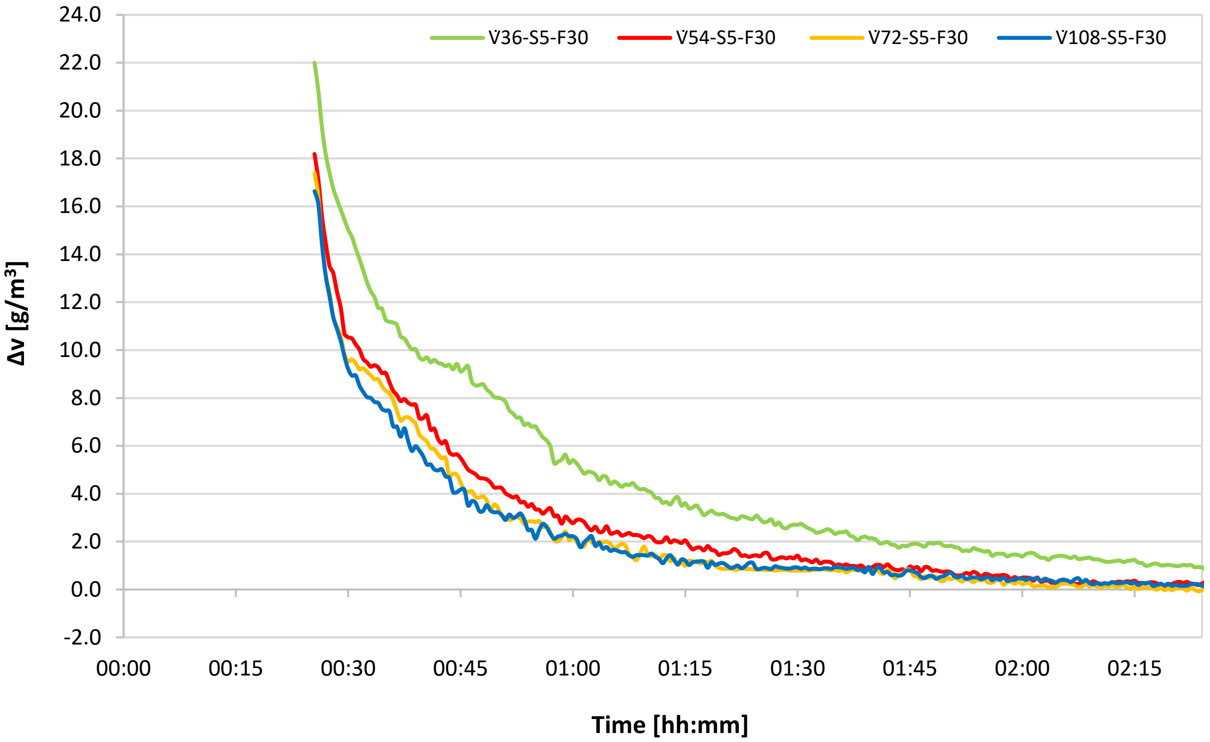


Figure 30: Moisture level near the roof monitoring position 12. at ventilation rates of 36 m³/h, 54 m³/h, 72 m³/h, and 108 m³/h with constant slit (5mm) and underfloor heating (30 °C).

Furthermore, the figure 31 below shows the experiments conducted with slit 15 mm and underfloor heating turned on at 30 °C. The ventilation air flow rates 54 m^3/h and 72 m^3/h behave in a similar manner from the end of shower sequence until the duration of the drying process. Ventilation air flow rate with 108 m^3/h is significantly quicker in the drying process and this could be due to high suction from the ventilation that the moisture load is immediately mitigated out from the bathroom before the moisture has the chance to spread and move around the bathroom. Ventilation air flow rate 36 m^3/h again shows the slowest drying process.

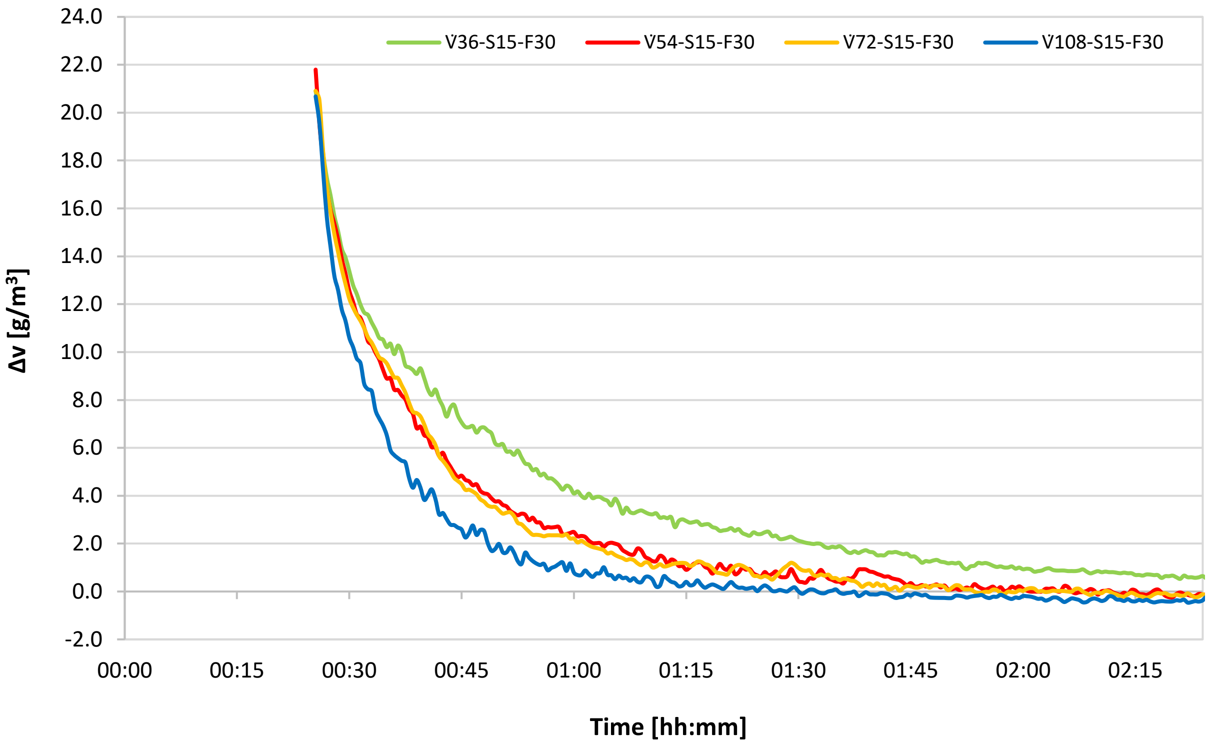


Figure 31: Moisture level near the roof monitoring position 12. at ventilation rates of 36 m³/h, 54 m³/h, 72 m³/h, and 108 m³/h with constant slit (15mm) and underfloor heating (30 °C).

Moreover, the figure 32 shows an increase in the underfloor heating temperature to 33 °C while slit (15 mm) remains the same as in figure 31. Increasing the underfloor heating temperature does show to have a slight impact on the drying process as the higher ventilation air flow rate appear to be much closer to each other. After an hour, the higher ventilation rates start to obtain the stationary conditions in the bathroom. This is further discussed and illustrated in section 6.1.

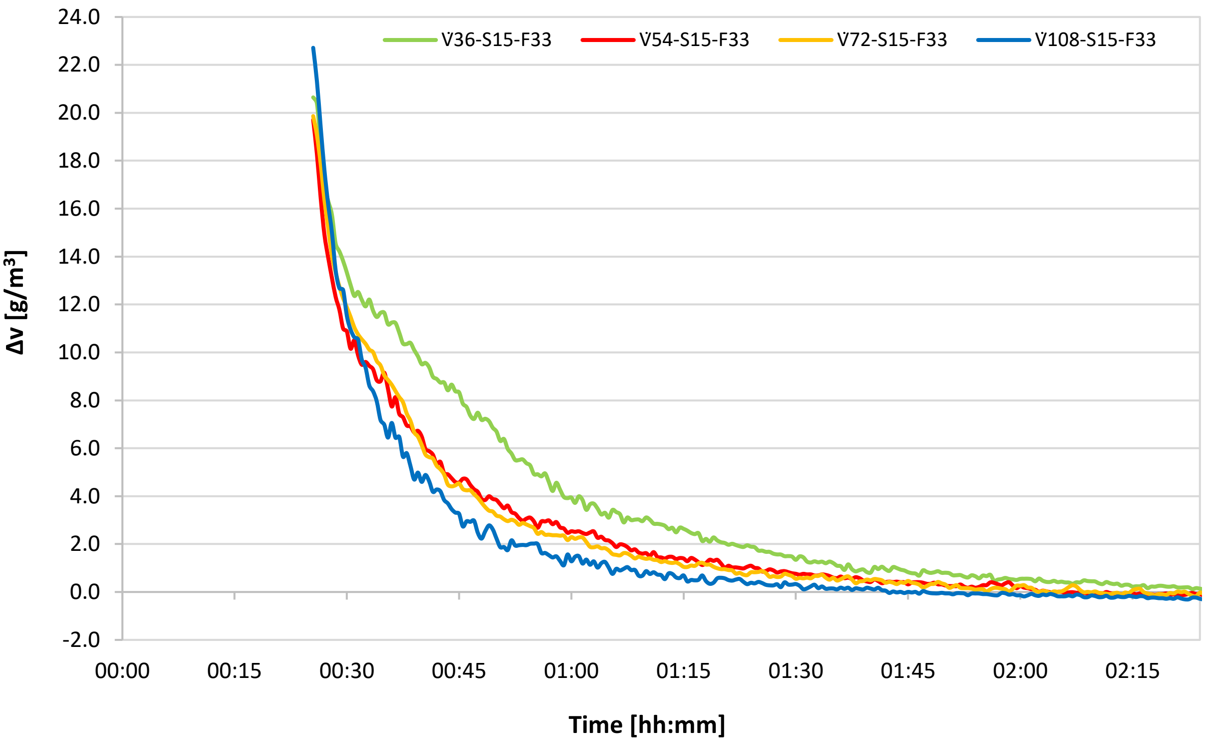


Figure 32: Moisture level near the roof monitoring position 12. at ventilation rates of 36 m³/h, 54 m³/h, 72 m³/h, and 108 m³/h with constant slit (15mm) and underfloor heating (33 °C).

In the final week of the experiments, a series of experiments including ventilation air flow rates of 54 m^3/h and 72 m^3/h with 30 mm slit under the door and 30 °C underfloor heating was performed. The reason these particular ventilation air flow rates were chosen (other than due to time constraints) was because the patterns from the previous experiments displayed in figures 28-32, showed that 108 m^3/h yields the most significant drying time therefore it was of interest to investigate the drying time of 54 m^3/h and 72 m^3/h that are much closer to each other. Both curves show rapid drying time and one of the reasons that this is the case is because of the slit 30 mm and underfloor temperature at 30 °C, again showing that the slit difference is a significant contributor towards the drying process. After the one hour mark the experiment appear to have obtained the same rate of drying.

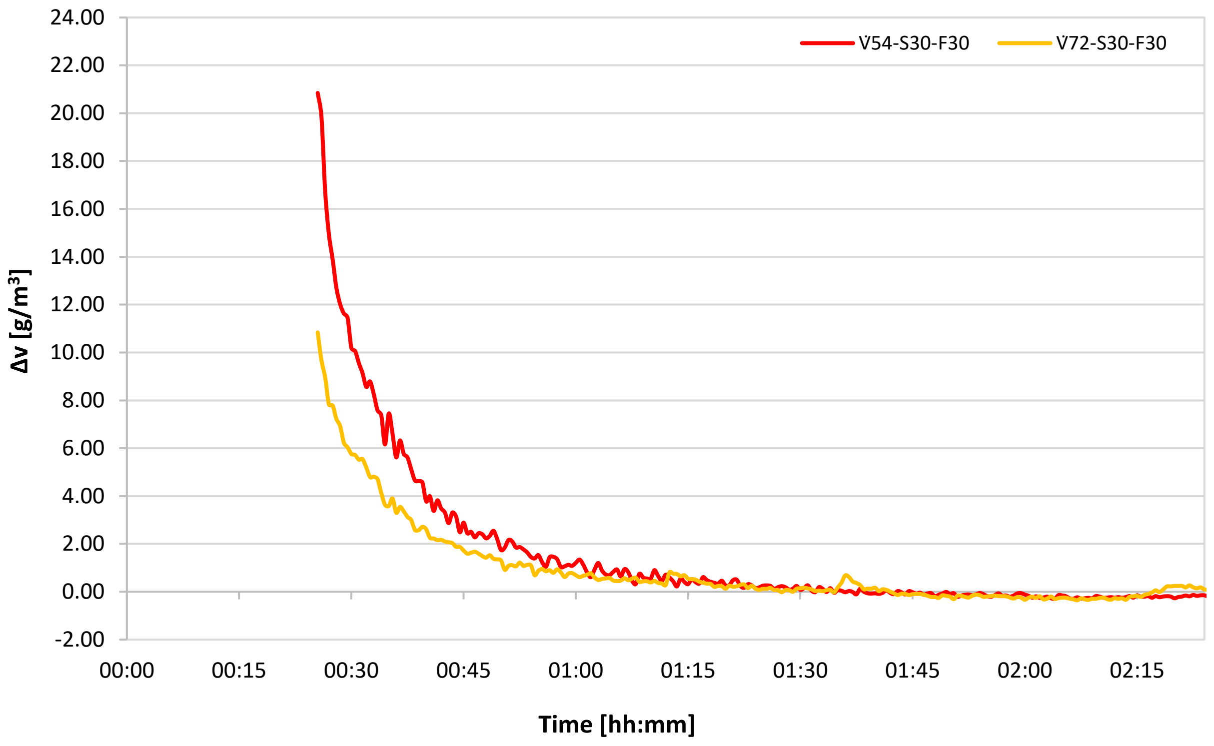


Figure 33: Moisture level near the roof monitoring position 12. at ventilation rates of 54 m³/h and 72 m³/h with constant slit (30mm) and underfloor heating (30 °C).

5.2 Spatial resolution of air temperature and relative humidity

5.2.1 Air temperature

The development of the air temperature illustrates how it operates during and after shower events, shown in figure 34 from 5 different Tinytag sensors until the end of the drying process. The experiment that is shown in the figure 34 below is the worst-case scenario with ventilation flow rate at 36 m^3/h, slit 5 mm and with no underfloor heating, as described in section 5.1.

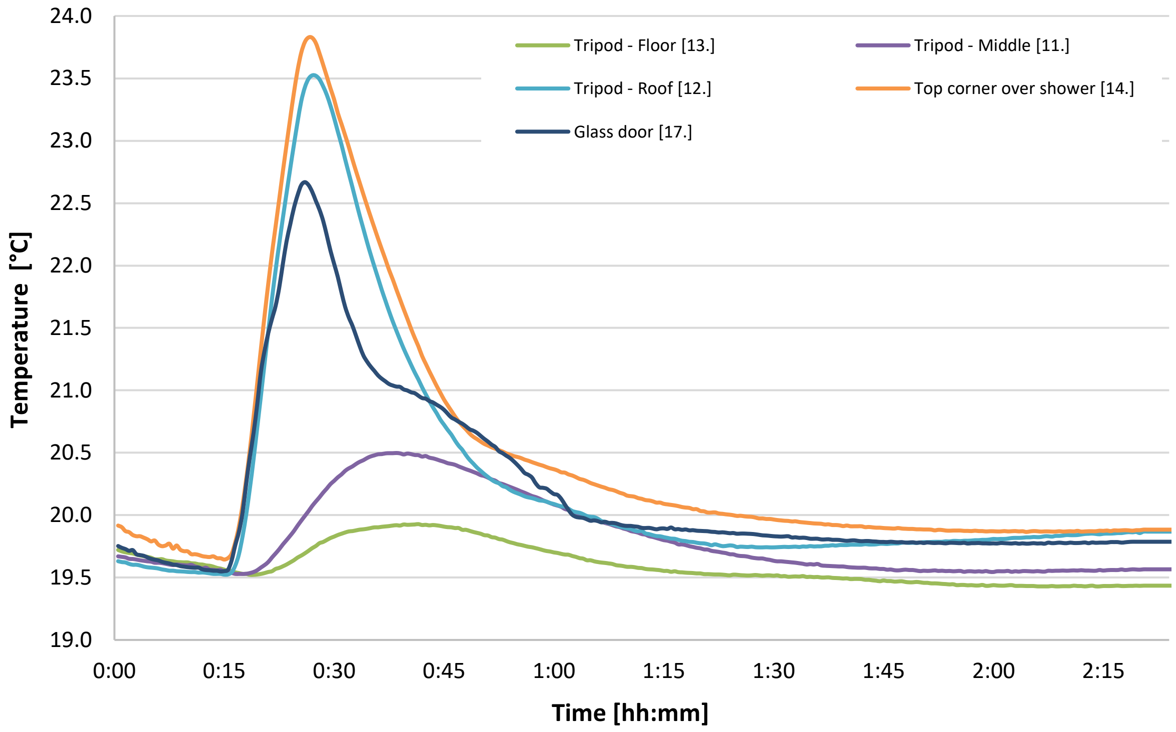


Figure 34: Air temperature from five different Tinytag sensors showing experiment with slit (5 mm), underfloor heating (off) and ventilation air flow 36m³/h

The figure 34 depicts that the air temperature increased right after the shower was turned on and continued to increase until it had been turned off, for all sensors. This shows that all the sensors inside the bathroom had similar response time. The air temperature increased by approximately 4.5 °C and it took roughly more than an hour and 30 minutes before returning to the initial state that the bathroom was in before the shower event started.

The sensor position 11. was used to determine the room air temperature because it is in the middle of the bathroom. It varied from 19.5 to 20.5 °C for the duration of the experiment. This is lower than the desired comfortable room air temperature based on the theory section, in the bathroom.

However, the air temperature increase is different for each sensor. For example, the sensor that is placed on top corner over shower head (position 14.) shows the most significant increase but the sensor placed in the middle of the bathroom on the floor (position 13.) shows the least significant increase in the air temperature that is between 19.5 to 20 °C during the experiment, as underfloor heating was off.

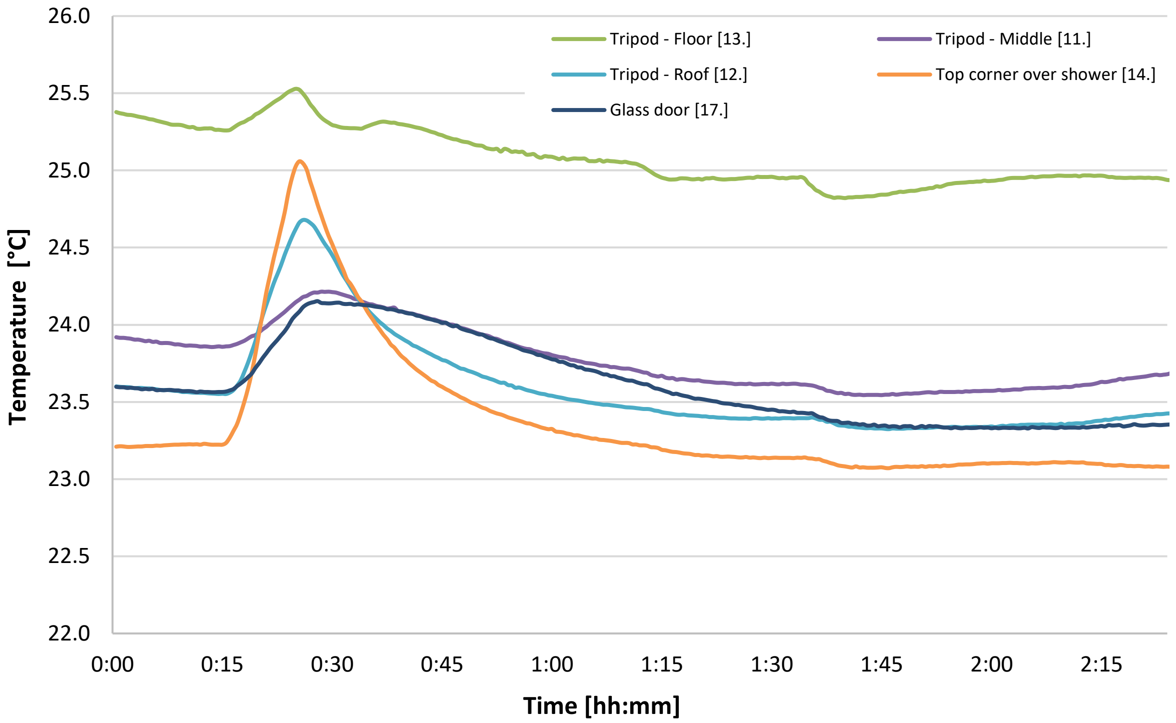


Figure 35: Air temperature from five different Tinytag sensors showing experiment sensors with slit (30 mm), underfloor heating (30°C) and ventilation air flow 72m^3/h

Furthermore, comparing the same Tinytag sensors with another experiment that yielded optimal results with ventilation rate 72 m^3/h, slit 30 mm and underfloor temperature 30 °C, based on section 5.1. Hence, the figure 35 above shows the inside air temperature in the bathroom is approximately between 23.5 to 24.2 °C this is shown by the sensor placed on the tripod middle (position 11.). Rationally the sensor placed at tripod floor (position 13.) shows the most significant increase in the temperature as the underfloor heating is now turned on. In addition, the pattern in the increase of air temperature repeats itself when comparing figure 34 and figure 35, the only difference being that the inside temperature is higher in figure 35 and much closer to the desired comfortable bathroom air temperature as described in the theory section.

5.2.2 Relative humidity

The relative humidity is now shown in figure 36 for the same experiment that showed the air temperature in the previous figure 34. The figure 36 shows the sensors (position 12. & 14.) that were placed tripod roof and top corner over the shower head had relative humidity at 100% for the longest time compared to the other sensors within the bathroom. This is due to these sensors are the closest to the moisture source (shower head). These two sensors show that the relative humidity holds 100% for 26 minutes from when the shower sequence started. Due to insignificant air movements inside the bathroom as the slit length was 5 mm, ventilation flow rate was 36 m^3/h, and no underfloor heating.

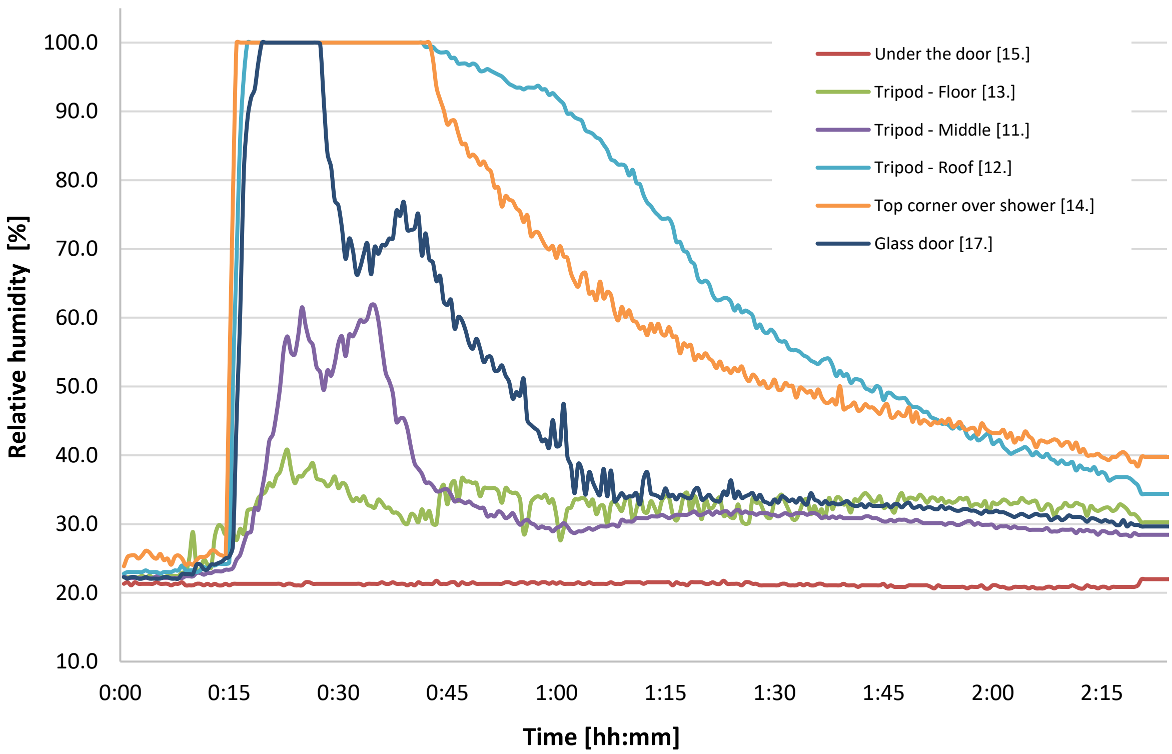


Figure 36: Relative humidity from five different Tinytag sensors showing experiment sensors with slit (5 mm), underfloor heating (off) and ventilation air flow 36m³/h

Moreover, the sensor that was placed on the floor (position 13.) had insignificant changes in the relative humidity compared with the rest of the sensors that were placed higher up in the bathroom. The rest of the sensors showed significant spikes in the curves after the shower was turned on. This can be due to the small opening for under the door slit at 5 mm resulting in less fresh air that enters the bathroom and the lower ventilation rate at 36 m^3/h meaning less air is extracted from the bathroom. Therefore, it takes relative humidity much longer and stays in the bathroom for longer period before it is extracted.

Furthermore, comparing the same relative humidity sensors with a different experiment that gave optimal results that is with ventilation flow rate 72 m^3/h, slit 30 mm under the door and underfloor temperature 30 °C. Hence, the figure 37 below shows the relative humidity decreases significantly as compared to the previous figure 36. The major factor now being that the ventilation flow rate and the underfloor heating is increased. Comparing the tripod roof sensor (12.) does not obtained 100% relative humidity as it did in the previous experiment from figure 36. Meanwhile, the sensor (14.) placed above the shower head showed 100% relative humidity for 10 minutes (from the shower sequence started) before it rapidly decreased.

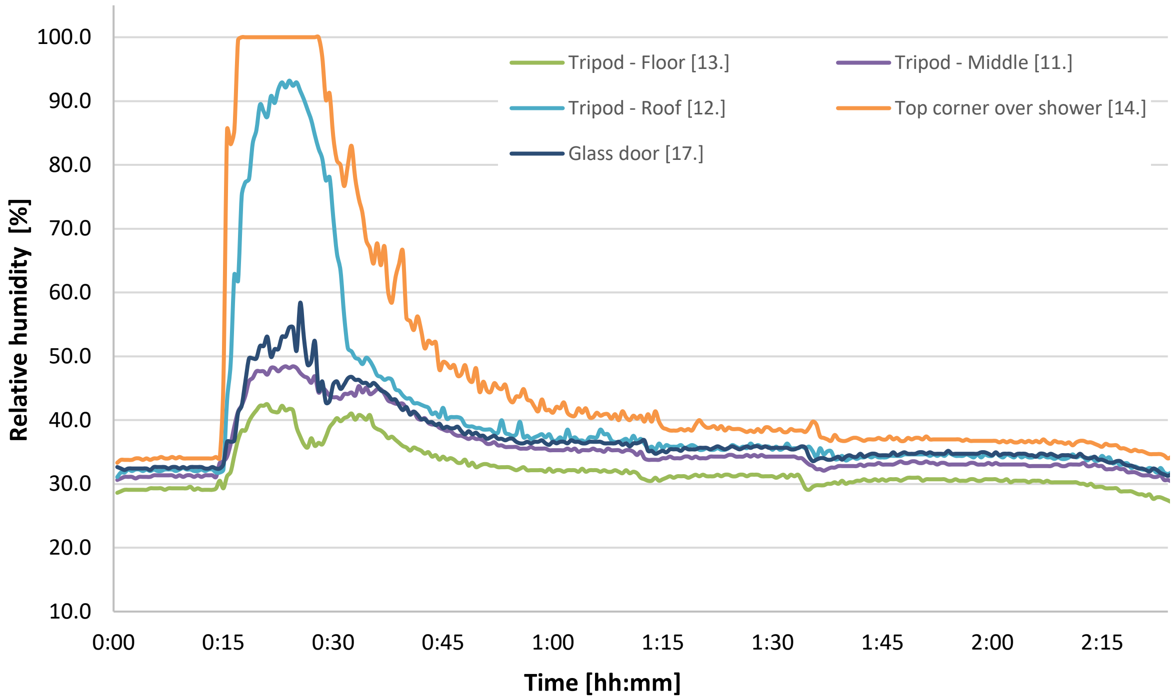


Figure 37: Relative humidity from five different Tinytag sensors showing experiment sensors with slit (30 mm), underfloor heating (30°C) and ventilation air flow 72m³/h

6 Discussion

When considering the previously mentioned studies, then in common they mentioned in using a greater range of parameters. Thus, this master thesis builds its basis upon their future recommendations and carried out experiments with greater parameter ranges.

Regarding the parameters that are shower length, water temperature, flow rate, and ventilation valve location over the shower then these parameters are determined from the previous literature studies mentioned in the state of art section 3. The reason the shower length is kept 10 minutes and not 5 minutes is because the former represents a more realistic time model for the shower event. Consequently, the water temperature for the shower is chosen to be 41 °C as this parameter is often repeated in the mentioned studies and based upon as the comfortable temperature for showering. The flow rate of the shower is at 100% as max flow rate of water is more realistic and suitable as it pushes the worst-case scenario approach. As for the location for the ventilation valve it was initially desired in this experiment to conduct two locations for the ventilation valves as one of the previously mentioned studies stated that investigating location at different positions on the roof might have yield different results. Subsequently, one study [75] did also mention that location of the ventilation valve is the least critical parameter therefore this assumption was carried out as in this master thesis due to time constraints it was not possible to investigate more than one valve location for the ventilation.

Hence, the authors will first shed more light upon the sections presented in the results and then discussing the uncertainties, limitations, and challenges faced and how it impacted the experiments.

6.1 Parameters that affect drying time

The results showed that the increase in the value of any of the parameters (ventilation flow rate, slit and underfloor heating) is directly proportionate with the drying process, however each parameter is not equally significant when increased. This is illustrated in the section 5.1.

To summarise the drying time for each experiment for ease of comparison then table 11 below shows the time it took for each experiment to dry out in the bathroom. As described earlier in section 5.1. that the dry time was considered when bathroom reached the same moisture levels after the shower event had ended and reached the moisture level that was present in the bathroom before the shower event started. The table is sorted after the ventilation air flow rates.

Four of the initial experiments are seen as reference points that are namely with 5 mm slit and underfloor heating turned off conducted in the second week (appendix H). This will show the significant determination for each parameter. The reason these four are taken as reference points is because they yield the longest drying time in their respective ventilation air flow rates.

Table 11: Drying time for all the experiments expressed in percentage form and sorted after the ventilation rates, the four initial experiments are taken as reference point for the rest of the ventilation rates. The colours indicated in the table coincide with the figures presented in results, section 5.1.

Experiment number.		Dry time (min)	Percentage
1.	$\dot{V}$36-S5-F0	116	REF.
5.	$\dot{V}$36-S15-F0	97	16 %
9.	$\dot{V}$36-S5-F30	76	34 %
13.	$\dot{V}$36-S15-F30	68	41 %
17.	$\dot{V}$36-S15-F33	56	52 %
2.	$\dot{V}$54-S5-F0	96	REF.
6.	$\dot{V}$54-S15-F0	78	19 %
10.	$\dot{V}$54-S5-F30	51	47 %
14.	$\dot{V}$54-S15-F30	41	57 %
18.	$\dot{V}$54-S15-F33	41	57 %
21.	$\dot{V}$54-S30-F30	26	73 %
3.	$\dot{V}$72-S5-F0	66	REF.
7.	$\dot{V}$72-S15-F0	43	35 %
11.	$\dot{V}$72-S5-F30	40	39 %
15.	$\dot{V}$72-S15-F30	37	44 %
19.	$\dot{V}$72-S15-F33	37	44 %
22.	$\dot{V}$72-S30-F30	19	71 %
4.	$\dot{V}$108-S5-F0	42	REF.
8.	$\dot{V}$108-S15-F0	41	2 %
12.	$\dot{V}$108-S5-F30	36	14 %
16.	$\dot{V}$108-S15-F30	26	38 %
20.	$\dot{V}$108-S15-F33	25	40 %

The table 11 illustrates that experiment 1. took the longest time to dry as it had slit 5 mm, underfloor heating turned off and ventilation air flow 36 m^3/h. Taking this experiment as the reference point for the same ventilation rates. Thus, when the slit under the door is increased to 15 mm there is a percentage increase to 16% considering no underfloor heating. Consequently, increasing the underfloor temperature (30 °C) shows to yield an increase of 34% with 5 mm slit. However, increasing the slit to 15 mm with the same underfloor temperature (30 °C) gives 41% increase in drying time. Lastly, increasing the underfloor temperature to 33 °C with the same 15 mm slit then this gives an increase of 52% compared to the reference point.

Hence, the series of experiments with ventilation air flow rate of 36 m^3/h shows to be the most unsatisfactory combination in the bathroom compared to the higher ventilation air flow rates. As the drying time takes much longer time to obtain the initial stationary condition before shower event started. The sensors acquire the high relative humidity and air temperature for much longer periods.

Moreover, considering ventilation rates 54 m^3/h and 72 m^3/h yield similar patterns in drying time, shown in table 8. However, increasing the underfloor heating from 30 °C to 33 °C for these ventilation rates with 15 mm slits show the same percentage increase in both experiments. Nonetheless, experiment 22. had the fastest drying time at 19 minutes with slit 30 mm, underfloor heating 30 °C and ventilation air flow rate 72 m^3/h. However, the largest decrease in drying time was experiment 21. with 73% increase from the reference point, the only difference being the ventilation air flow rate at 54 m^3/h.

In addition, while comparing experiment 9.-12. with 13.- 16. where only the slit increases, one can evidently see that the drying time is significantly affected by this parameter (table 11). For example, experiment 10. shows a percentage increase of 47% from reference point but experiment 14. shows percentage increase of 57%. This means that when underfloor heating is turned on at the same temperature (30°C) then the increase in slit is more effective than the increase in underfloor heating. Comparing experiments 14. and 15. with 18. and 19. with the only difference being the underfloor heating from 30 °C to 33 °C shows that the drying time had little to no change thus further adding to the argument that the temperature increases in the underfloor is not as significant of a change when the gap under the door is increased.

One of the reasons that the change was not as significant can be due to the placement of the underfloor heating pipes; illustrated in figure 12 in section 4.3.1, the pipes are much warmer in the middle than they are nearer the corners and since the shower is placed in the left corner than this can impact the rate of evaporation. In contrast, the slit opening under the door allows the fresh air to enter and combat the moisture inside the bathroom released from showering, helps to mitigate moisture load. This as mentioned in the theory section would decrease the drying process.

Thus, as the ventilation air flow rate increases, the shorter the drying period. However, the ventilation air flow rate with 72 m^3/h and 108 m^3/h do not have much significant difference between the two. It depicts that the ventilation flow rate parameter is significant in determining the drying process in the bathroom, as 36 m^3/h shows slower drying process compared to 108

m^3/h that is very rapid. In addition, the drying process is even more rapid when the underfloor heating is turned on as shown in in table 11.

One of the considerations that the experiment neglected in totality was the human factor. As explained in the theory section that the human moisture production can vary from 30 to 300 g/h. Thus, realistically one rationale would be that human’s level of activity in showering can immensely impact the level of moisture level as the parameter being the level of physical activity that determines this and since the human body itself emits or is a source of heat. Thus, one argument can be that the drying process would increase if the human factor was involved.

6.2 Spatial resolution of air temperature and relative humidity

The development of relative humidity in the conducted experiments suggests that there is an instant decrease rate after couple of minutes of switching the shower valve off, considering the underfloor heating in turned on. As a result, the total time it takes for the relative humidity to achieve a stationary condition is approximately 2 hours. Thus, this is in contrast with one of the mentioned study [74] in the literature review that also required 2.5 hours to reach stationary levels after the shower event was ended.

The bathroom's entire air volume is continually being exchanged with receiving fresh air through the slit under the door and from the ventilation valve over the shower space. The air is only present for a set amount of time, assuming that the air inside the room is homogenous and thoroughly mixed. This is determined by the ventilation system's airflow rate, $\dot{V}$ m^3/h, as well as the room volume, V m^3. Hence, devising the formula for the air change rate of the room as:

$$n=\dot{V}/V$$

As recalling the ventilation rates for the experiments namely, 36 m^3/h, 54 m^3/h, 72 m^3/h, 108 m^3/h and the volume of the bathroom was 10.5 m^3. Thus, by utilizing the provided formula above the air change rate of the room was be calculated as respectively 3.4 h^{-1}, 5.1 h^{-1}, 6.8 h^{-1}, and 10.2 h^{-1}. The value calculated shows how long the air on average remains in the bathroom before it is exchanged out.

By making this observation of the relative humidity then this rationale is in accordance with the theory section. As illustrated in Figure 37 showcasing that the relative humidity begins to drop shortly after the shower is switched off. The decline happens at a set rate that is dependent on the ventilation rate that is evident in this case and assuming the size of the bathroom will also influence this rate. The relative humidity is significantly dependable upon the conditions that are inside and outside the bathroom. Meaning that when the outdoor relative humidity for the bathroom was low this condition corresponded within the bathroom as well. It can be due to that fact that the bathroom was not sufficiently insulated.

Furthermore, the supplied warm water from the shower, that is significantly warmer than the surrounding room air temperature then the heat energy is transferred from the warm shower water that is at 41 °C into the air. Thus, the energy from the shower is transferred to the materials and onto the bathroom’s floor and walls. This energy heats up the materials causing the air temperature inside the bathroom to rise. As heat transfer by convection and buoyancy begins as soon as warm water is released from the shower head, warm air rises thus the Tinytag sensors register higher air temperatures that are closer to the roof. Thus, the sensors that are placed closer to the middle and the floor do not have as higher air temperatures as compared to the roof sensors.

Moisture is discharged into the air as water vapor during a shower sequence. The relative humidity rises quickly to saturation and remains there as long as the rate of production exceeds the ventilation system's capacity. The moisture supply is withdrawn when the shower is turned off, and ventilation starts to take control. The ventilation system replaces the air in the room, diluting the created humidity at a rapid pace. However, as seen in Figure 33, the pace in drying time is increased and immediately changes less than a minute after the shower is turned off. To add further to that one can also see a transition period (for drying process) if looking at figure 37 that when the ventilation removes the water vapour released from the shower head then after approximately 30 minutes have gone by after the shower event was ended then there is a spike in the figure 37 this at point, that can be explained by that the evaporation of the liquid that could possibly take place in this period.

6.3 Uncertainty with measurements, and challenges

One of the main challenges was that the authors never got to observe the shower sequence event from inside the bathroom meaning all the experiments had to be performed and observations were based on the IR camera. However, it would have been important to observe how the moisture moves through the room when the shower sequence is ongoing. The authors did use the smoke test in the first week of the trials to make observations upon how the air in the room moves. It was evident from this empirical test that the vent over the shower pulled the air out and the slit under the door supplied fresh air.

When conducting the experiments, it is extremely critical that the instruments have great level of precision and accuracy. Thus, to confirm this, calibrations of all the instruments was conducted. This process was tediously time consuming but crucial for the tests. At first the relative humidity and air temperatures were lacking in logging the data however after the calibration had been done, this improved the response time. Errors in the measuring equipment could have likely distorted some of the data, for example one Hioki wire was connected into the shower head and over time this wire could have been damaged causing the sensor to read unstable values. As a result, reading wrong values for the shower water temperature. This problem occurred in the first week and had to be resolved by replacing the wire altogether.

Similarly, the most significant challenge was the test hall, the air temperature within the test hall varied from 15 – 22 °C. When the door of the test hall was open the temperatures within the test hall would at times drop below 15 °C, this is because the period of conducting the experiments were in late winter and early autumn season. Hence, the outside temperature was extremely cold and when the main hall door was opened for deliveries then the inner hall temperature would fall significantly. Therefore, it affected the specific humidity the air could absorb inside the bathroom. In addition, there were other bathroom test modules present in the hall that were under experimentation thus impacting the air temperature and relative humidity levels in the hall facility. This means that there were ongoing activities simultaneously at times in the hall facility that could have impacted the indoor conditions of the hall and consequently affecting the conducted experiments.

The installed door on the bathroom module was not a real door as one would see fitted in a bathroom. Therefore, the door was not as insulated and sealed as it would be in a residential apartment building as it was opened at slightly different angles and was lifted from the ground. Subsequently, impacting the maximum value of the moisture content in the air during each measurement thus making comparison between the values very difficult. However, this could have been avoided by adjusting the angle and height of the door that is more realistic.

Furthermore, regulating the heat from underfloor was a challenge because the thermal inertia of the concrete floor made it difficult to adequately make predictions when the temperature had stabilized at the desired specified level. Therefore, margins were taken into consideration and left the underfloor heating on for the following day to give it enough time to stabilize the temperature on the floor. In addition, the bathroom module has been exposed to outside temperature prior to coming to the SINTEF lab and no information was given for how long it was exposed to outside temperatures in the winter. The module is made from concrete and has the ability to store energy at a slow rate for a given period of time.

Another challenge was defining what is considered a sufficiently dry area, since the experiments were performed twice a day every 3 hours then this could have potentially impacted the moisture logging of the following experiment in the afternoon after conducting the first experiment. In addition, the humidity on the shower floor shows to be slightly higher than the humidity measured at the supply air, indicating that the moisture stored near the floor joints, surface water near drainage may be the one of the reasons for high difference in maximum value of moisture at the start of each measurement. This can be shown in the comparison between the values from early morning test to the afternoon test, while the early morning tests have greater period for the bathroom to dry out all night than the afternoon test.

Mainly tape was used to remove unnecessary wiring dangling around the bathroom floor and walls, thus after some of the shower events it was observed that water was present in the tape because it was wet. Hence, storing moisture in the tape and this affected the relative humidity values as they decreased and prolonging the time for the bathroom to dry. Along with the wetness of the tape, another critical observation was that small quantity of water was trapped on the top of the glass door walls. Since this was in the middle of the room then it took slightly longer for the water to evaporate considering with underfloor heating on then the floor dried up more quickly and because of the floor the droplets of water are more spread out and tinier. Moreover, glass doors were much thicker and bigger in size as compared to a normal glass door for showers in a residential bathroom. The curvature of the glass doors was formed in a rectangle shape and not in a semi-circle shape as they would be in a residential bathroom and thus the semi-circle shape allows for better drainage of the water from the shower and an easier path. As compared to a rectangle than the splashed water would spread into unwanted gaps in the bathroom.

Moreover, the condensation that occurs on the surfaces outside the wet zone such as on the mirrors and the glass doors, have dew that evaporates again when heated. Thus, it will have a net energy intake of zero i.e., balanced enthalpy process. Meaning the evaporation that initially occurs after showering and thus it will not increase the drying time and alter the calculation during the process. In addition, to avoid moisture damage it is advantageous to have a shower cabinet walls, however this does not in any case represent accurately the design choice of residential apartment as some may not have cabin showers. This is an active choice and preferability from the users as some might like to shower on the tiles. As well as the regulation and recommendation for the wet zone is minimum of 1:50 on the floor and in essence due to the viscous forces the water droplets that will be left on the floor after showering is not assumed they will completely evaporate from the floor. There will always be few droplets that may be hard to observe present after evaporation time. Water layer results in a lower ratio of exposed surface to water volume, resulting in less air exposure and, as a result, less efficient evaporation and, ultimately, a longer drying time.

The absorption of moisture is achieved by the diffusion of water vapour molecules and the flow of water from water levels into the material's pores. It is difficult to keep control of the water intake and outtake and hence the evaporation and the movement of moisture out through the exhaust is more interesting for this thesis. Thus, the variable is difficult to account for when numerous measurements are conducted in quick succession. Lastly, the surface material on the walls and floors are primarily concrete and tile finishing however, residential apartments can have different surface materials. Therefore, this thesis only takes into consideration the given test module materials.

In addition, the original plan that was devised in the beginning had experiments that would involve measuring the moisture buffering of towels and finding out how they will affect the moisture levels within the bathroom. However, due to time constraints and hindrance then the authors were not able to get the instrument required to collect data for this particular secondary experiment. Nonetheless, this is something that can be investigated in the future, as this study sets the basis for further investigation into moisture buffering.

Nevertheless, there were few difficulties considering the test hall as the authors only had access to the hall from between 0800 until 1700 this meant that for some of the experiment that were performed late were not able to collect the data on the same day and added further delay to the process.

7 Conclusion

This master thesis investigated the various parameters in the bathroom module that included primarily mechanical ventilation flow rate, underfloor heating temperature and slit under the door. The objective was to determine if any of these mentioned parameters affected the moisture level and the drying time in bathrooms.

It was determined that changing the ventilation rate shows to cause the most effective change in the moisture levels in the bathroom. As the moisture levels decrease with faster drying process. In addition, as expected when the underfloor heating is turned on, then the drying time also decreases however there is not much significant difference between the underfloor heating temperatures 30 °C and 33 °C. The typical drying time was found to be within 40 to 50 minutes that occurred more frequently in this study. Consequently, the shortest drying time was found to be at 19 minutes that had the combination with ventilation air flow rate 72 m^3/h, 30 mm slit under the door and underfloor heating at 30 °C. Therefore, if any increase in the parameters (ventilation air flow rate, slit and underfloor heating) would lead to a decrease in the drying time and vice versa.

Regarding the spatial distribution of air temperature and relative humidity, it showed that all the sensors recorded different values in the bathroom. Meaning that the measurements of the sensors depend on the air distribution movements inside the bathroom. It was found that if one increased the underfloor heating temperature then this resulted in increase in air temperature, obtaining the desirable room air temperature. The sensors closest to the moisture source (position 12. & 14.) held the relative humidity for the longest time in all the experiments.

Meanwhile, when considering a slit increase 5 - 30 mm, the increase in slit under the door shows that the drying process decreases as one increase the gap beneath the door. Considering these findings then only one of the studies mentioned in the literature review that had investigated two different slit lengths. In addition, another study had underfloor heating but only compared it to limited combinations of the parameters. Therefore, this master thesis presents a holistic approach with all the three main parameters that none of the previously mentioned studies have attained.

8 Recommendation for future work

Regarding recommendation for future work, then isolating the bathroom test module from the test hall and covering it with a tent such that there is a more realistic model with better insulation. As was the case in this master thesis, there was significant heat loss with the underfloor heating as the bathroom was lifted from the ground causing air in the hall to flow under it. With isolation of the bathroom, one would also have more constant outside temperatures and thus improving the accuracy of the measurements.

The energy used for the ventilation/underfloor heating, as the higher the ventilation rate the more energy it is required and with the current economic conditions rising energy usage is a concern for the average users. This can have an impact upon the user's choice for underfloor heating. Even though this master thesis suggests certain 30 °C underfloor heating, however one user might find that to be costly.

Key improvements in the bathroom module as previously mentioned with the bathroom door and the shower glass walls inside were not as realistic. Thus, making such improvement can yield better results and in addition these experiments could have also been performed in living labs. For example, nowadays there are more stylish bathrooms with fancy lighting on the mirrors. Our bathroom did not have a bathmat, storage basket or toilet papers. There are many objects that were readily missing from our bathroom module.

Thus, based on the conducted research as presented in this study, the next step would have been to investigate the impact of moisture buffering to add further knowledge to this area. As moisture buffering can be used to reduce the amount of moisture released from the shower, thus this theoretically will impact the drying time and moisture level. Hence, this investigation can provide whether moisture buffering is an effective way to deal with moisture. One way to do this would have been with using textile towels in the bathroom and monitoring the change of weight of the towel from the start of the shower event to achieving the initial state of conditions in the bathroom.

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10 Appendix

All the figures shown in this section are private archives captured by the authors using their own mobile phone cameras and sketches made by the authors to present in this section.

A - Bathroom test module

B - Setups for the test module

C - Smoke test

D - Thermal images from IR camera

E - Tinytag calibration

F - Mass flow rate of mixer valve and mass flow rate of circulation pump

G - Heat loss

H - Weekly experimental plan

I - Experimental Procedure

J - Documentation k-factor for the relevant measuring cross (Bass swema)

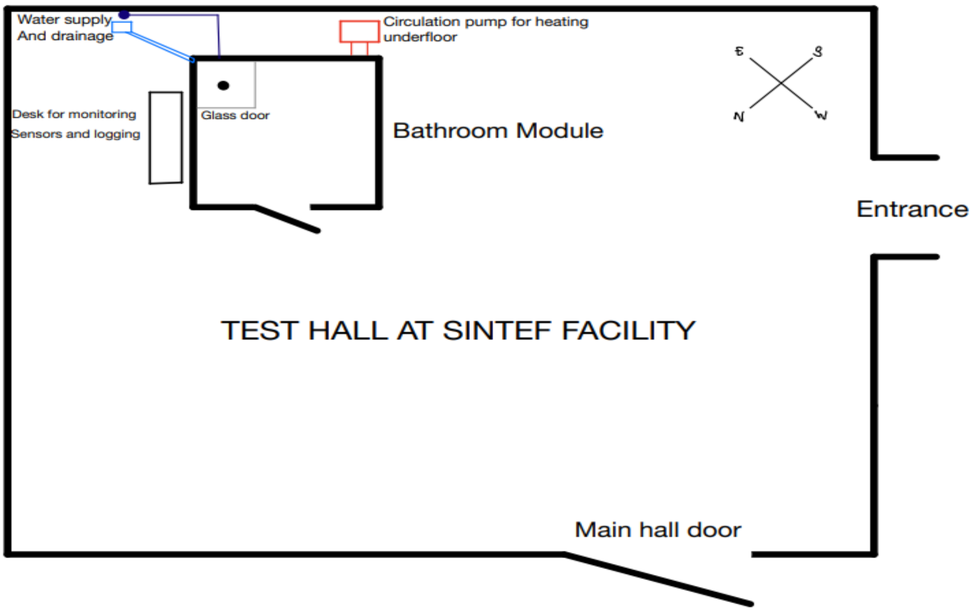
K - Calibration Swemaflow 125

L – Moisture level results

M – Spatial results

A - Bathroom test module

A visualization of the SINTEF test hall facility



The bathroom module when it arrived at the SINTEF facility

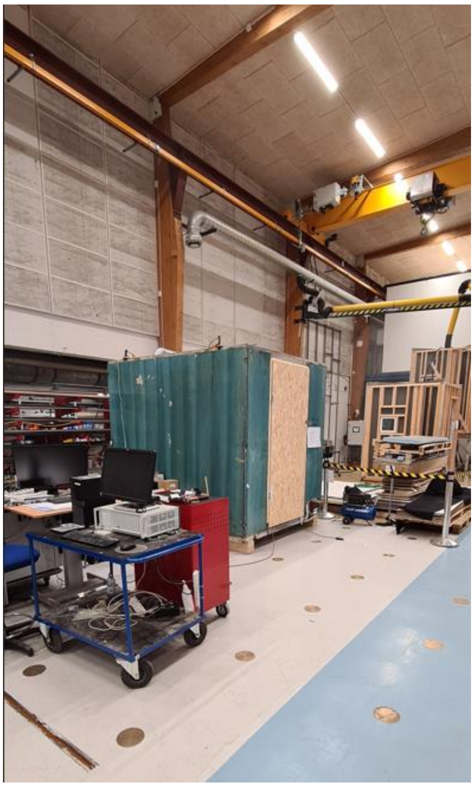
B - Setups for the test module

Setting up door, mixing valve, circulation pump and Drainage system

Setting up ventilation exhaust

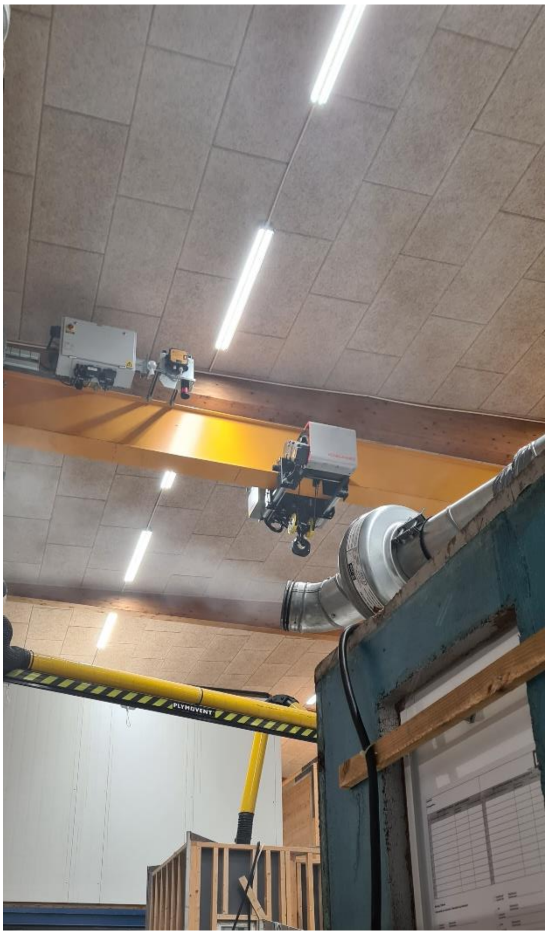
Setting up shower head, hall sensor/placement



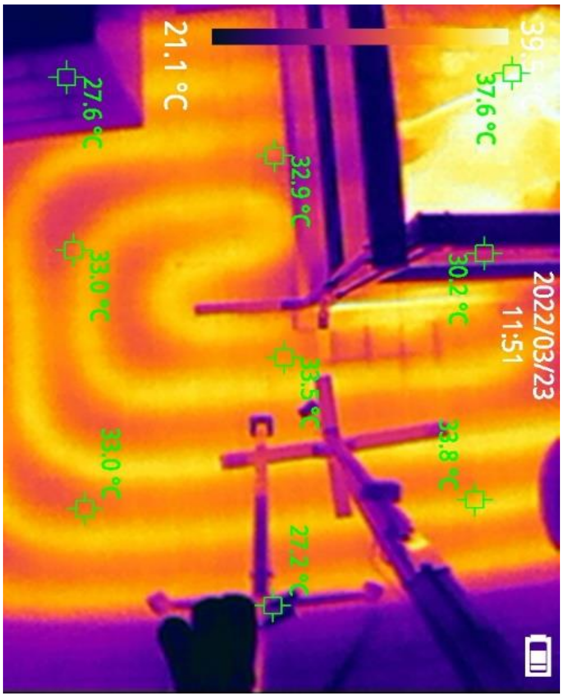


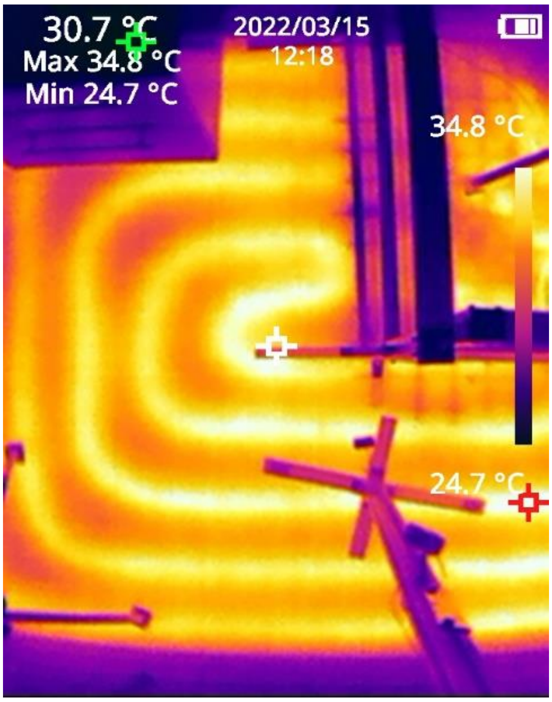

Equipment used during the experiment

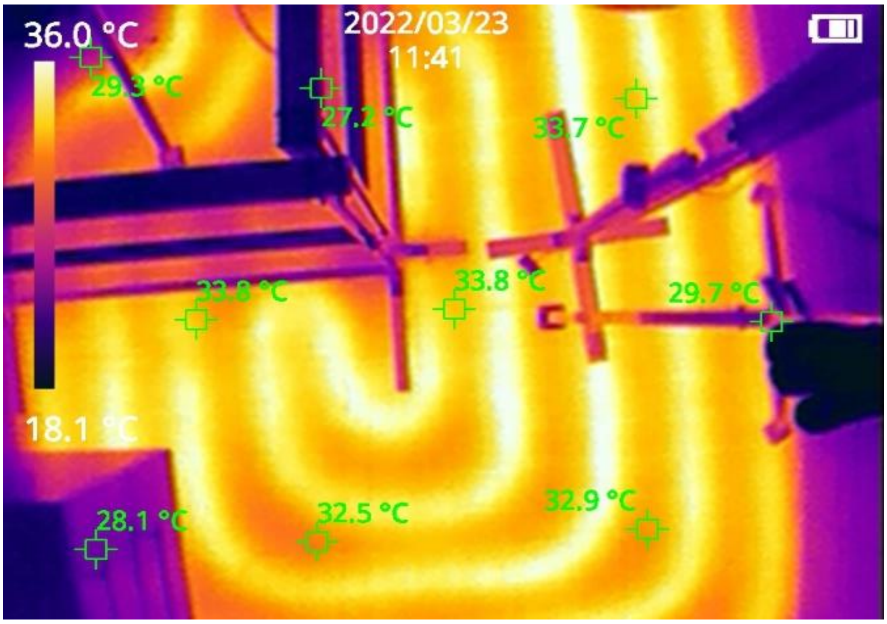
C - Smoke test



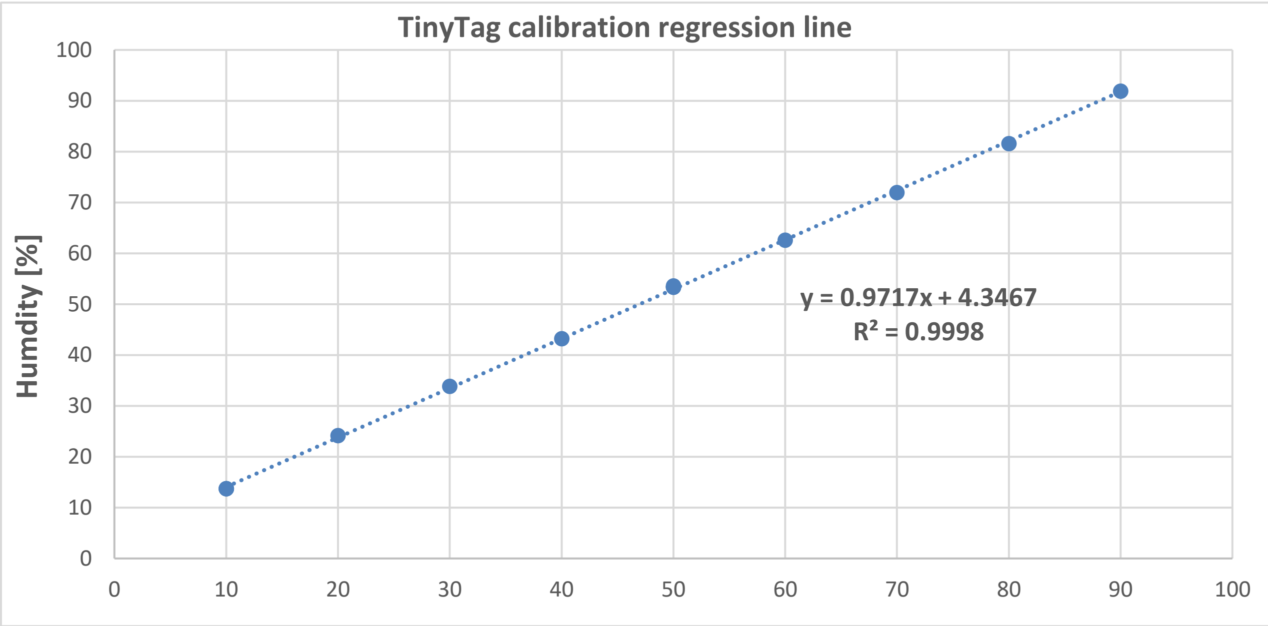
D - Thermal images from IR camera







E - Tinytag calibration



F - Mass flow rate of mixer valve and mass flow rate of circulation pump

Mass flow rate of mixer valve

Time (Sec)	Weight (litre)		
30	4.828	9.656	l/ min
30	4.736	9.472	l/ min
30	4.852	9.704	l/ min
	Average	9.61	l/ min

Antatt verdier hentet fra nettside		
[Varmekabler innendørs | Elektroimportøren AS (elektroimportoren.no)](elektroimportoren.no)		
I følge nettsiden anbefales det (120 - 150)W/m^2		
Kabin gulvareal	4.5	m^2
Gulvvarme	150	W/m^2
Dermed er <Kapasiteten på varmeelementet "s	675	W
	1 W	1 J/s
Kapasiteten på varmeelementet "som" tilføres	675	W
		=
	675	J/s
Spesifikk varmekapasitet vann	4.18	J/gK
Ønsket temperaturfall på vannet (delta T)	4	°C eller (K)
Dette betyr vi kan ut Ca.	17	J/g
	1	g/s
		=
	0.06	L/min
Menge vi må sirkulere på	40.3	g/s
Dette tilsvarer	2.4	L/min

Mass flow rate of circulation pump

Time (Sec)	Weight (litre)		
10	1.542	9.25	l/ min
20	3.018	9.05	l/ min
30	4.396	8.79	l/ min
40	5.746	8.62	l/ min
50	7.144	8.57	l/ min
60	8.67	8.67	l/ min
	Average	8.83	l/ min

G - Heat loss

	Symbols	Values	Units
Temperature in LAB hall	T_{out} (°C)	21	K
Temperature inside cabin (bathroom)	T_{inn} (°C)	25	K
Wall/Ceiling/Roof thickness	d	0.04	m
Wall area	A_{wall}	20	m^2
Ceiling/Floor area	$A_{ceiling/Floor}$	4.5	m^2
Thermal conductivity	λ	2.5	(W/mK)
AirFlow	V	54	m^3/h
Air Density		1.3	kg/m^3
Specific air heat capacity	c	1005	kJ/kg

	Units	Walls	Ceiling	Floor	Ventilation
Temperature in LAB hall [T_{out}]	K	25	25	25	25
Temperature inside bathroom [T_{inn}]	K	21	21	21	21
Internal surface [Rsi],	$(m^2K)/W$	0.13	0.1	0.17	
Thickness [d]	m	0.04	0.04	0.04	
Thermal conductivity [λ]	(W/mK)	2.5	2.5	2.5	
Thermal resistance [R=d/ λ]	$(m^2K)/W$	0.016	0.016	0.016	
External surface, [Rse]	$(m^2K)/W$	0.04	0.04	0.17	
U-value	W/m^2K	5.38	6.41	2.81	
Air Flow [V]	m^3				54
Density	kg/m^3				1.3
Specific heat capacity [c]	kJ/kg				1005
Area	m^2	20	4.5	4.5	
Heat loss	W	430.11	115.38	50.56	77.93

Total Heatloss	**673.98 W**

H - Weekly experimental plan

WEEK 1								
Variables	Monday (07.03.2022)		Tuesday (08.03.2022)		Wednesday (09.03.2022)		Thursday (10.03.2022)	
	W1-D1		W1-D2		W1-D3		W1-D4	
	A36-S15-F0		A54-S15-F0		A72-S15-F0		A108-S15-F0	
Shower length (minutes)	10	10	10	10	10	10	10	10
Water temperature (°C)	41	41	41	41	41	41	41	41
Airflow (m³/h)	36	36	54	54	72	72	108	108
Flow rate (%)	100	100	100	100	100	100	100	100
Slit under the door (mm)	15	15	15	15	15	15	15	15
Underfloor heating (°C)	Off	Off	Off	Off	Off	Off	Off	Off
Exhaust location	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower

WEEK 2								
Variables	Monday (14.03.2022)		Tuesday (15.03.2022)		Wednesday (16.03.2022)		Thursday (17.03.2022)	
	W2-D1		W2-D2		W2-D3		W2-D4	
	A36-S5-F0		A54-S5-F0		A72-S5-F0		A108-S5-F0	
Shower length (minutes)	10	10	10	10	10	10	10	10
Water temperature (°C)	41	41	41	41	41	41	41	41
Airflow (m³/h)	36	36	54	54	72	72	108	108
Flow rate (%)	100	100	100	100	100	100	100	100
Slit under the door (mm)	5	5	5	5	5	5	5	5
Underfloor heating (°C)	Off	Off	Off	Off	Off	Off	Off	Off
Exhaust location	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower

WEEK 3								
Variables	Monday (21.03.2022)		Tuesday (22.03.2022)		Wednesday (23.03.2022)		Thursday (24.03.2022)	
	W3-D1		W3-D2		W3-D3		W3-D4	
	A36-S5-F30		A54-S5-F30		A72-S5-F30		A108-S5-F30	
Shower length (minutes)	10	10	10	10	10	10	10	10
Water temperature (°C)	41	41	41	41	41	41	41	41
Airflow (m³/h)	36	36	54	54	72	72	108	108
Flow rate (%)	100	100	100	100	100	100	100	100
Slit under the door (mm)	5	5	5	5	5	5	5	5
Underfloor heating (°C)	30	30	30	30	30	30	30	30
Exhaust location	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower

WEEK 4										
Variables	Monday (28.03.2022)		Tuesday (29.03.2022)		Wednesday (30.03.2022)		Thursday (31.03.2022)		Friday (01.04.2022)	
	W4-D1		W4-D2		W4-D3		W4-D4		W4-D5	
	A36-S15-F30		A54-S15-F30		A72-S15-F30		A108-S15-F30		A54-S30-F30	
Shower length (minutes)	10	10	10	10	10	10	10	10	10	10
Water temperature (°C)	41	41	41	41	41	41	41	41	41	41
Airflow (m³/h)	36	36	54	54	72	72	108	108	108	108
Flow rate (%)	100	100	100	100	100	100	100	100	100	100
Slit under the door (mm)	15	15	15	15	15	15	15	15	15	15
Underfloor heating (°C)	30	30	30	30	30	30	30	30	30	30
Exhaust location	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower

WEEK 5										
Variables	Monday (04.04.2022)		Tuesday (05.04.2022)		Wednesday (06.04.2022)		Thursday (07.04.2022)		Fri day(08.04.2022)	
	W5-D1		W5-D2		W5-D3		W5-D4		W5-D4	
	A36-S15-F33		A54-S15-F33		A72-S15-F33		A108-S15-F33		A72-S30-F30	
Shower length (minutes)	10	10	10	10	10	10	10	10	10	10
Water temperature (°C)	41	41	41	41	41	41	41	41	41	41
Airflow (m³/h)	36	36	54	54	72	72	108	108	108	108
Flow rate (%)	100	100	100	100	100	100	100	100	100	100
Slit under the door (mm)	15	15	15	15	15	15	15	15	30	30
Underfloor heating (°C)	33	33	33	33	33	33	33	33	30	30
Exhaust location	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower	Over shower

I - Experimental Procedure

The measurements were conducted for over a period of six weeks. A daily routine was formed where in each day either two or three sequences for the tests were carried out. The following steps were taken each day:

1. Check the experiment plan for the day on the excel and see which parameters needs to be altered on the given day. This means changing either the ventilation rate, slit or adjusting underfloor heating.
2. Measure the ventilation rate using Swema air thus controlling the right ventilation rate is obtained.
3. Place the correct slit opening under the door.
4. Check all the Hioki wires for control and make sure every wire is registering data.
5. Set the shower head in the correct position along with the doll's head, ensuring that the interior glass door is in the correct 90 ℃ position. In addition, make sure the stationary tripod in the middle of the room is in the correct position.
6. Collect and transfer the data from all the loggers from the previous measurements to the computer, reading each device (Tinytags, CP11) with a USB and recording it on excel spreadsheets, same goes for Hioki using a memory stick.
7. Reprogram the loggers to retrieve data every 30 seconds and collecting a certain amount of data depending on the sequence. Set a delay start time for Tinytags such that the loggers start simultaneously after the door is closed.
8. Place all the loggers into their stationary positions.
9. Close the bathroom door, sealing it well.
10. Obtain the correct temperature on the mixer tap before connecting the hose to the shower inside the bathroom, meaning using the Hioki device control the temperature of the water supply.
11. Turn on the water tap on full pressure at the correct temperature for the specified experiment and wait for shower sequence to be over.
12. Using a stopwatch to monitor the time. Let the water run for the given period either 5 or 10 minutes.
13. Meanwhile observe the Hioki device and write down observations
14. After the period is over, close the water tap and wait for the evaporation time. Depending on the experiment.
15. After few hours open the bathroom door and repeat from step 1.

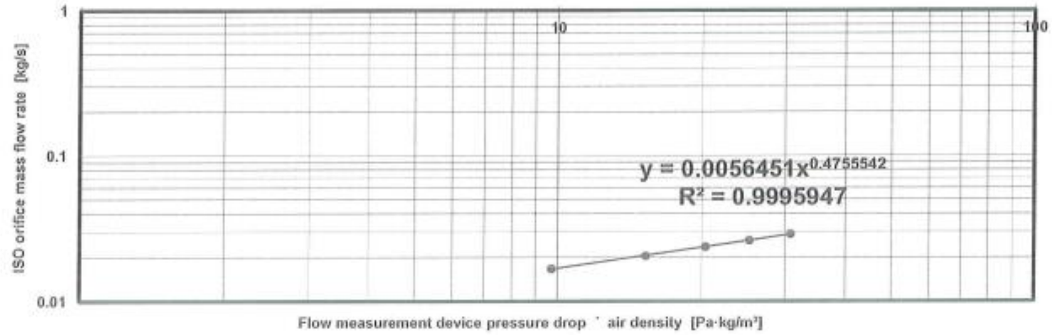
J - Documentation k-factor for the relevant measuring cross (Bass swema)

SINTEF — *ISO 5167-2:2003 calibration of differential pressure air flow rate measurement devices*

Instrument name/no. BAAS Ø100-ventil nr. 1 på VAV-rigg — Calibration conducted by: P.G.Schild

Manometer for ISO orifice	DPM (ny 2006)			
Manometer for test device	Swema 3000			
Dry bulb air temperature	21.5 [°C]			
Relative humidity	13 % [%]			
Barometric pressure	1002 [mbar]		Humidity ratio	1.9904E-05 [kg/kg]
Duct internal diameter (D)	104 [mm]		Air density	1.18465231 [kg/m³]
ISO orifice tappings type	Corner [-]		Dyn. viscosity	1.7977E-05 [Pa·m]

ISO orifice diameter (d) [mm]	ISO-orifice Δp [Pa]	Calibrated pressure (Δp) [Pa]	Test device (Δp) [Pa]	Calibrated pressure (Δp) [Pa]	True mass flowrate (m) [kg/s]	True volume flowrate (V) [ℓ/s]	True flowrate @1.2 kg/m³ [ℓ/s]	Reynolds # (Re_D) [-]
47	99.8	99.8	8.2	8.2	0.01671726	14.11153672	13.9310538	1.14E+04
47	151	151	12.9	12.9	0.02051274	17.31540729	17.0939477	1.40E+04
47	201	201	17.2	17.2	0.02362968	19.94651039	19.6913997	1.61E+04
47	248	248	21.3	21.3	0.02621885	22.13210788	21.849044	1.79E+04
47	302	302	26.0	26.0	0.02890433	24.39900075	24.0869439	1.97E+04



Summary		If n is assumed to be exactly 0.5 then:	
k_m^* =	**0.0056451 [kg/s]**	k_m^* =	0.00525467 [kg/s]
k_v^* =	**5.5985133 [ℓ/s]**	k_v^* =	5.2546675 [ℓ/s]
k_v^* =	**20.154648 [m³/h]**	k_v^* =	18.916803 [m³/h]
n =	**0.4755542 [-]**	n =	0.5 [-]

Mass flow rate : $\dot{m} = k'_m (\Delta p \cdot \rho)^n$ [kg/s]

Volume flow rate : $\dot{V} \equiv \frac{\dot{m}}{\rho} = \frac{k'_m}{\rho}(\Delta p \cdot \rho)^n$ [m³/s] $= k'_v \left(\frac{\Delta p}{\rho}\right)^n$ [ℓ/s]

$\dot{V}$ at reference $\rho = 1.2$ kg/m³ : $\dot{V}_{\rho=1.2} \equiv \frac{\dot{m}}{1.2} = \frac{k'_m}{1.2}(\Delta p \cdot \rho)^n$ [m³/s] $= k'_v \frac{\rho}{1.2}\left(\frac{\Delta p}{\rho}\right)^n$ [ℓ/s]

(assuming same mass flow rate)

K - Calibration Swemaflow 125

SINTEF

KALIBRERINGSBEVIS

Oppdragsgiver:
SINTEF Community

N-0 Oslo

Gateadresse:
Børrestuveien 3

Kontaktperson:
Eskild Svee Dahl

Vår ref:
O 423/22-61188

Serienummer:
366719

Fabrikat:
SwemaFlow 125

Instrumenttype:
HA

Merknader:
Instrumentet ble ikke justert.

Eskild Svee Dahl
2022.03.28
16:18:53 +02'00'

Neste kalibrering:
27.09.2022

Kal.dato:
28.03.2022

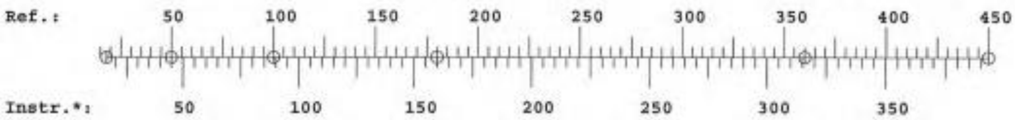
Kalibrert av:
ESD

Lufttemp. i lab.:
20,5 °C

Luftfukt. i lab.:
21,8 %RF

Barometertrykk:
997 hPa

18 - 450 m3/h



Referense	Instrument	Korreksjon	Avlest
18,00	16,00	2,00	
50,00	45,00	5,00	
100,0	89,0	11,0	
180,0	160,0	20,0	
360,0	316,0	44,0	
450,0	393,0	57,0	

18 - 450 m3/h

Børrestuveien 3 Postboks 124 Blindern 0314 Oslo Telefon:40 00 51 00 e-post:kalibrering.byggforsk@sintef.no

SINTEF

SPORBARHET

Barometer
Type: Coreci KC2585
Serienummer: 1153524
ID-nummer: 3724

Mikromanometer 0-2000Pa
Type: Furness PPC500
Serienummer: 0202012
ID-nummer: 3728

Temperatur- og luftfuktighetsføler
Type: Vaisala HMP233
Serienummer: R5120017
ID-nummer: 3732

Blendestrekk ISO 5167-2
Type: Blendestrekk 104mm
Serienummer: 4904
ID-nummer: 4904

Blendestrekk ISO 5167-2
Type: Blendestrekk 152mm
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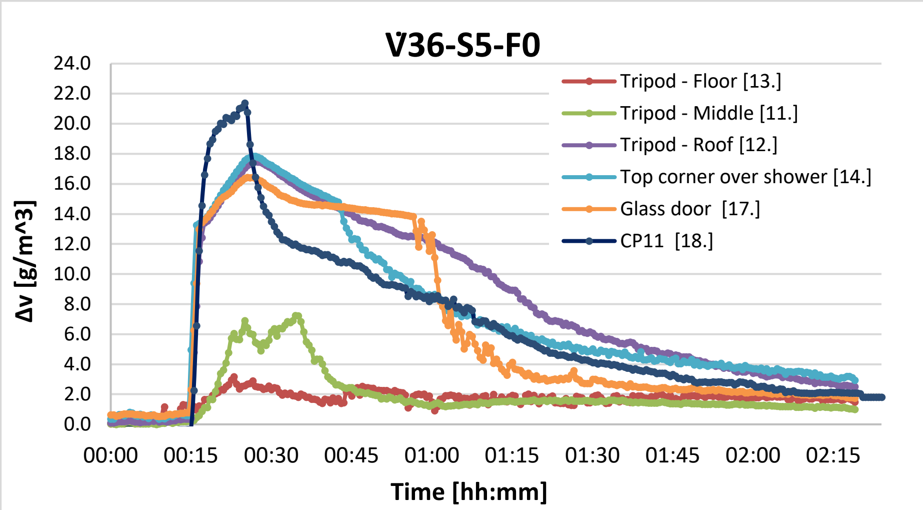
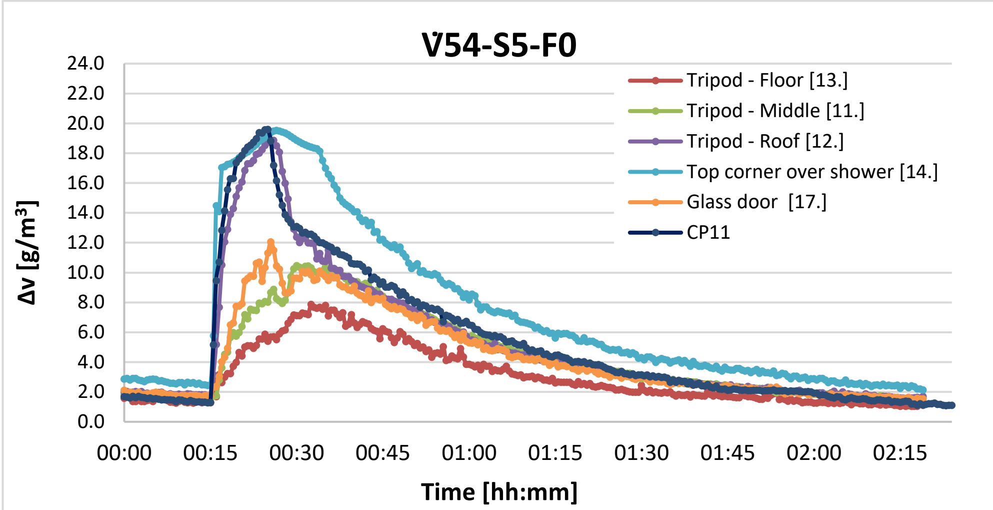
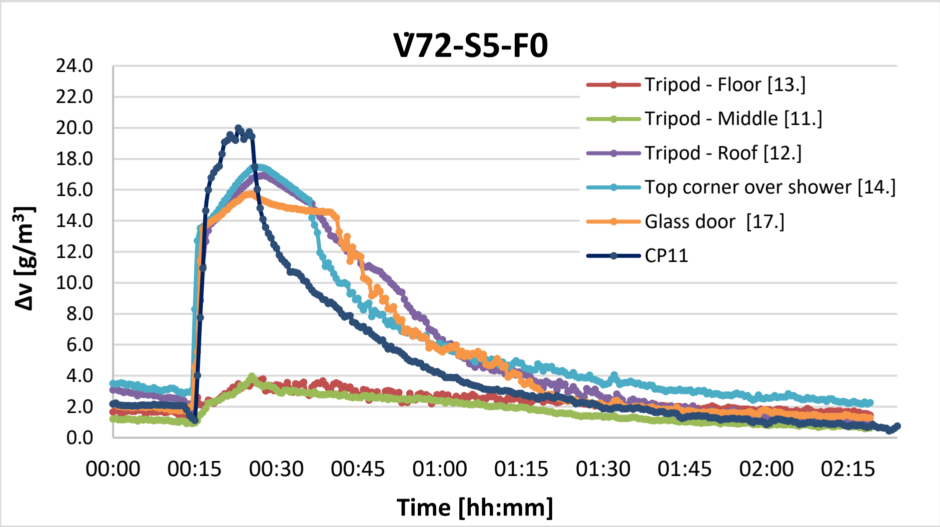
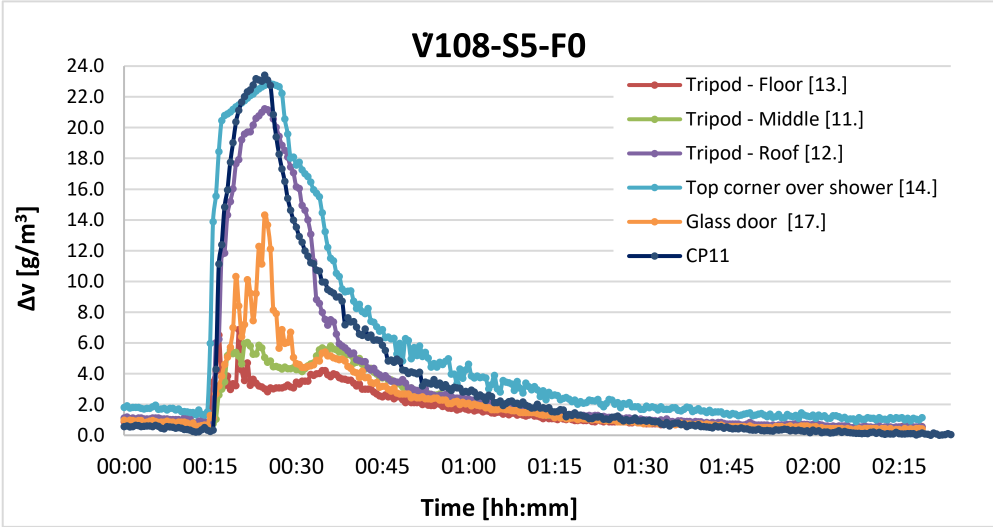
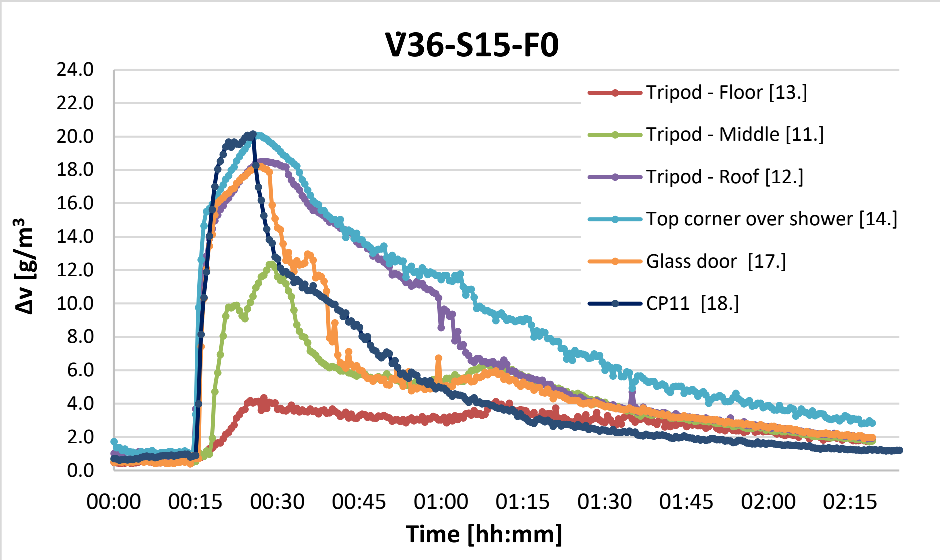
L – Moisture level results

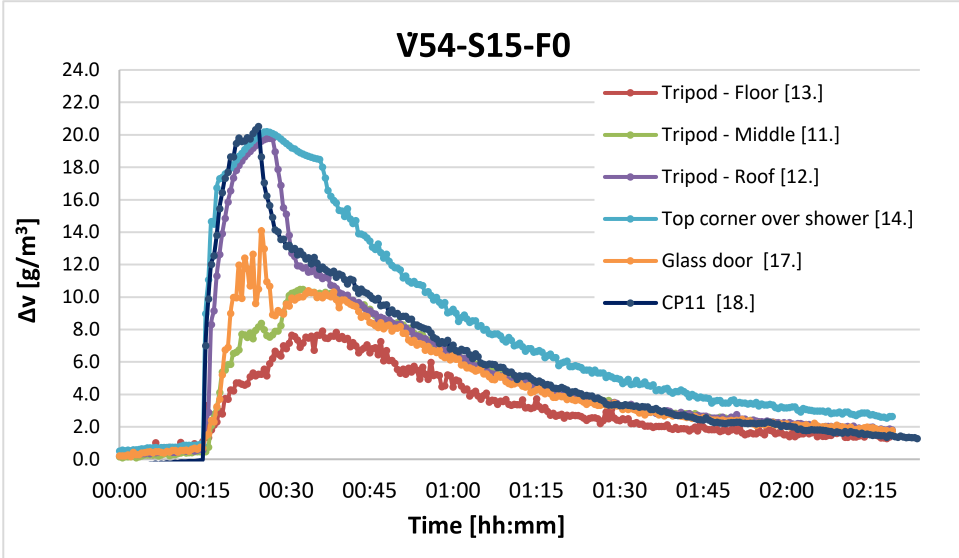









V36-S15-F0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Δv [g/m³]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]


V54-S15-F0
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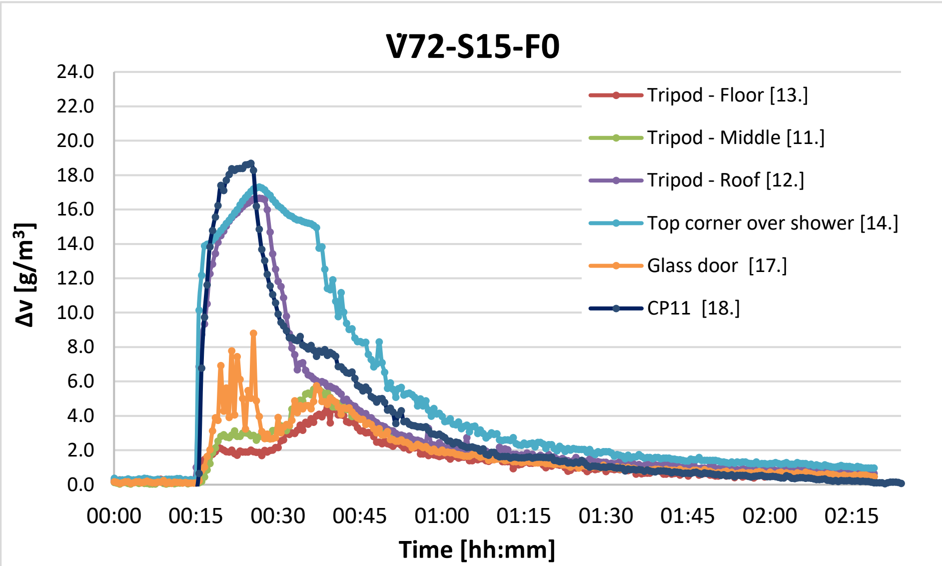
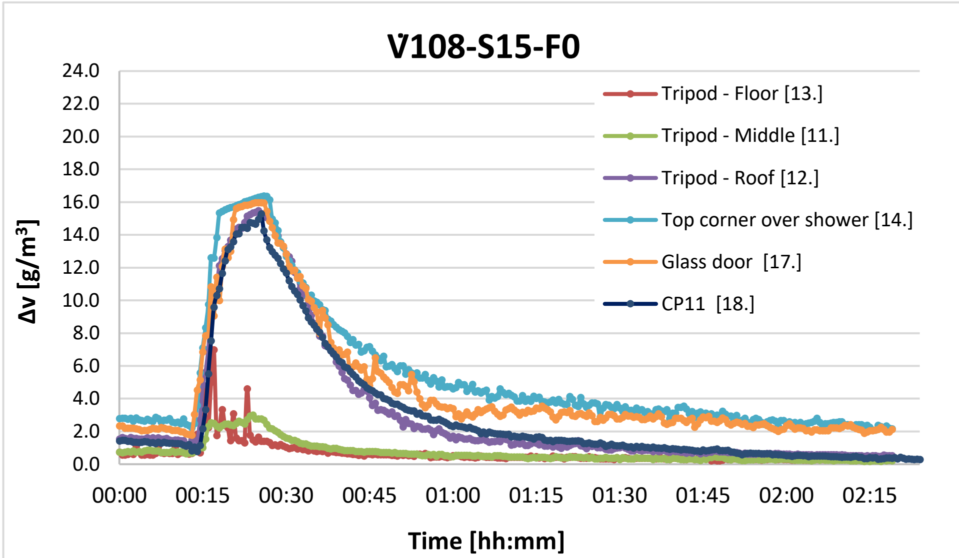
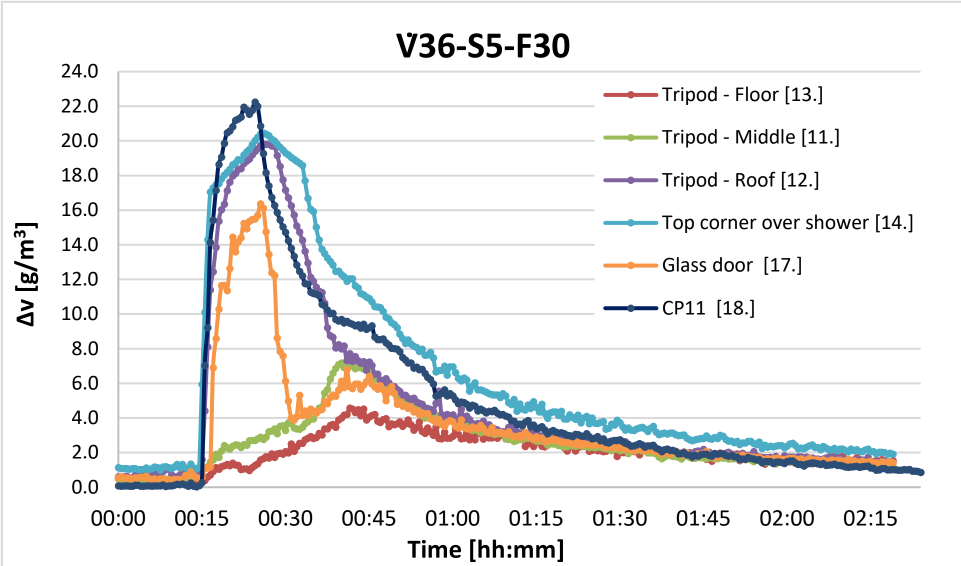
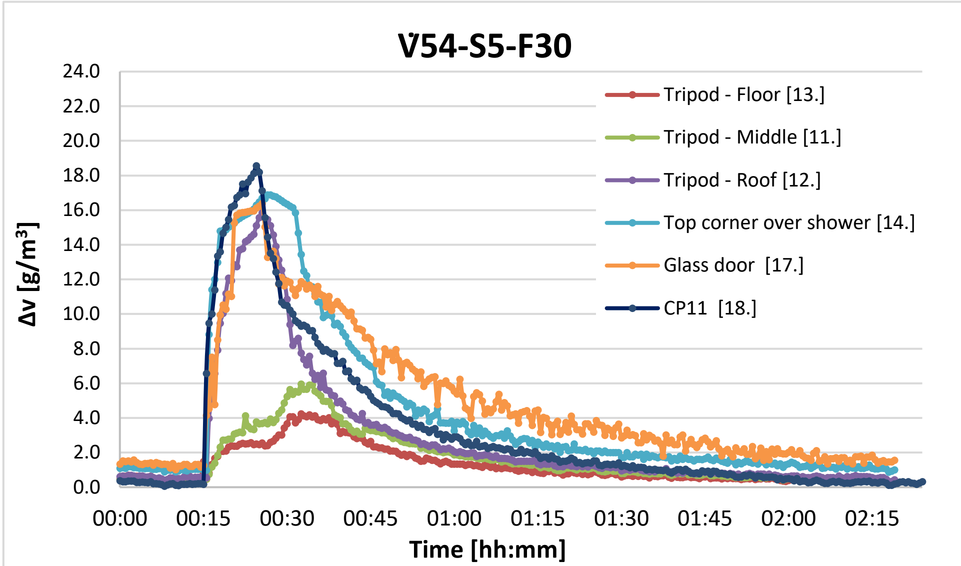
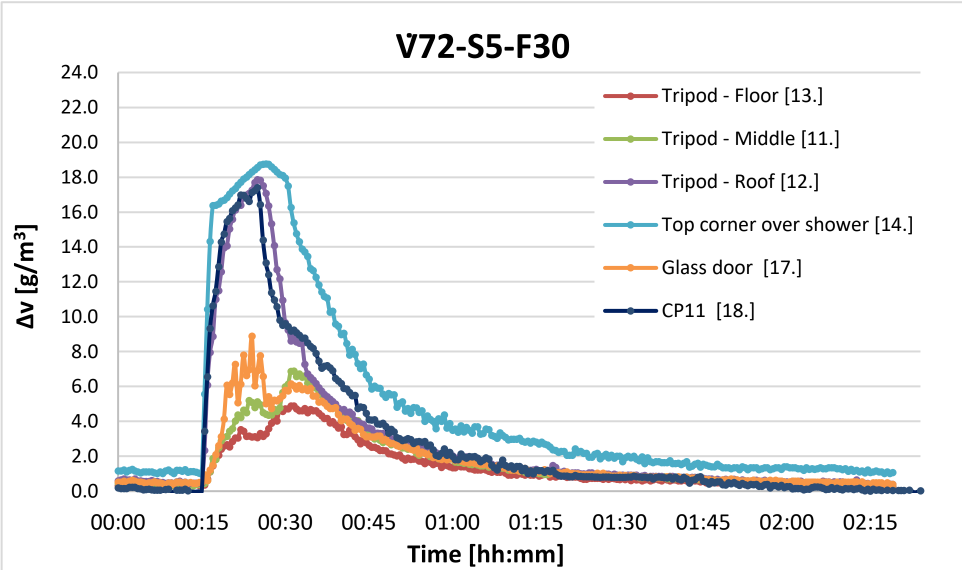
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Δv [g/m³]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

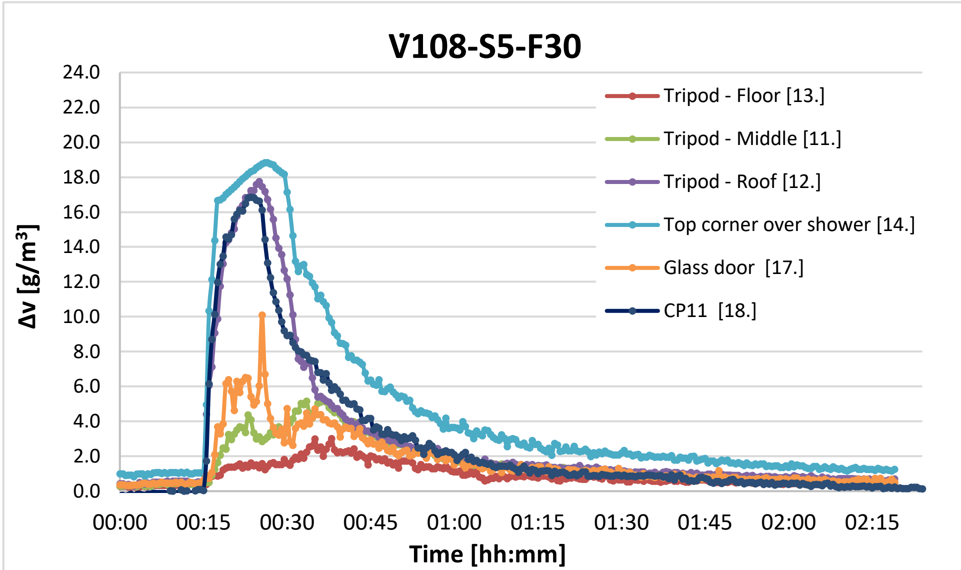

V72-S15-F0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Δv [g/m³]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

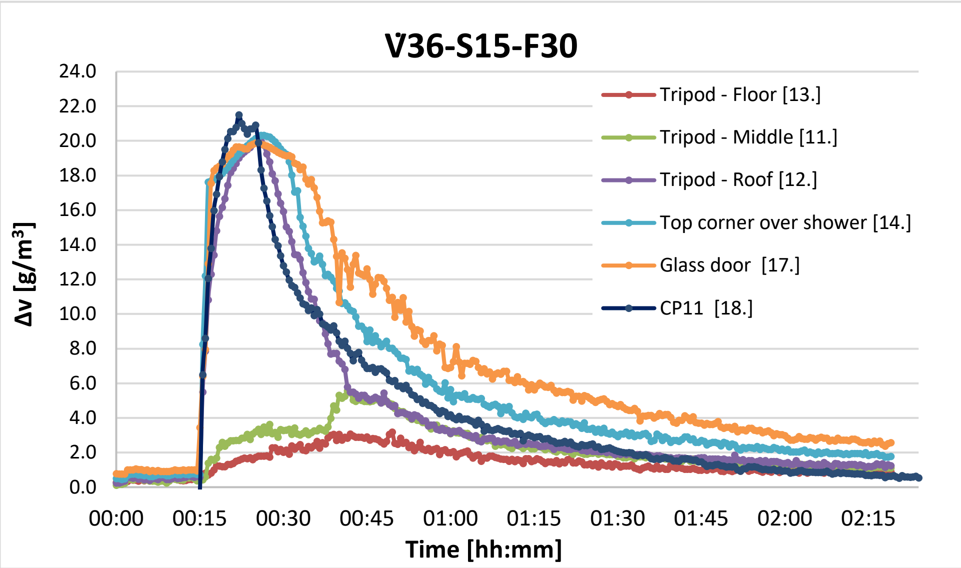

V108-S15-F0
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
Δv [g/m³]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

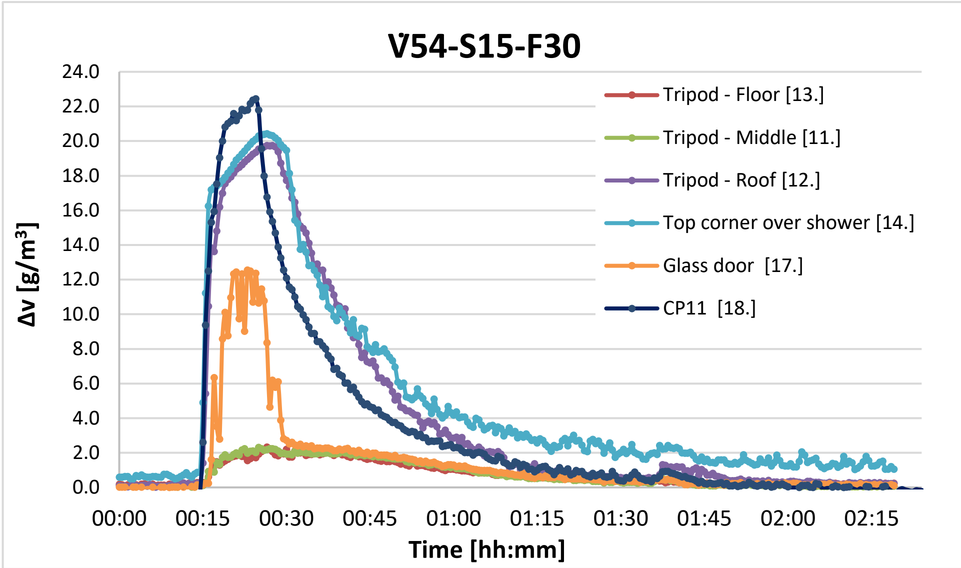

V36-S5-F30
Δv [g/m³]
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

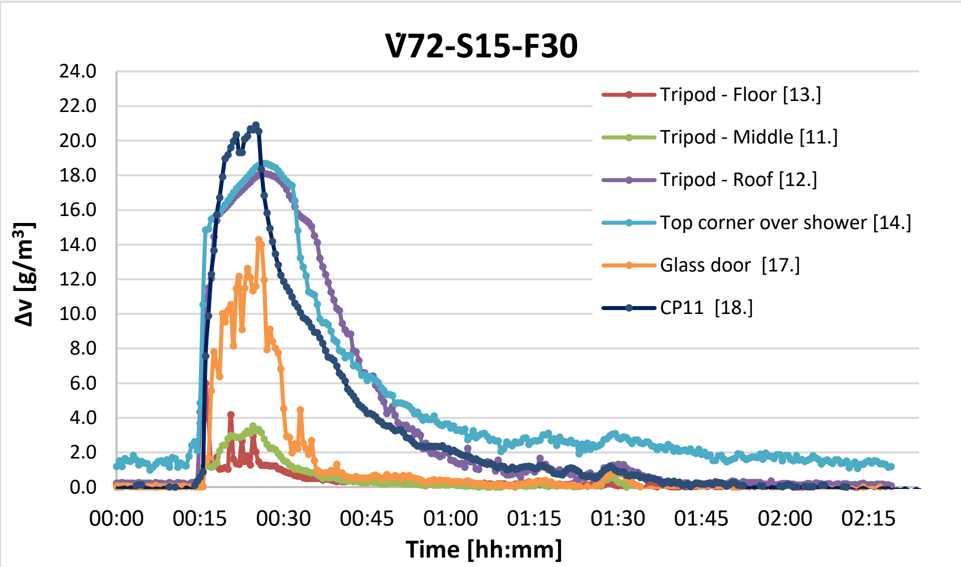

V54-S5-F30
Δv [g/m³]
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

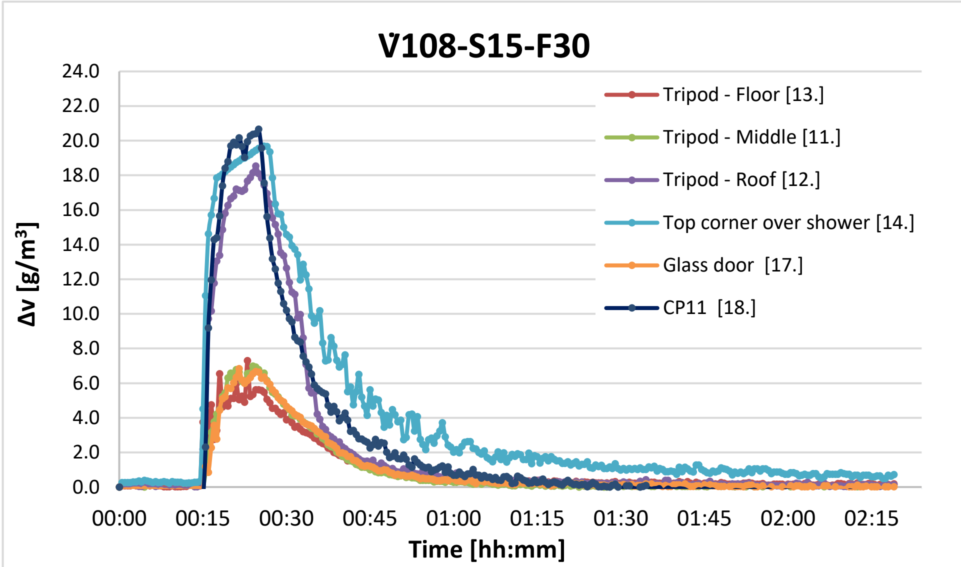

V72-S5-F30
Δv [g/m³]
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

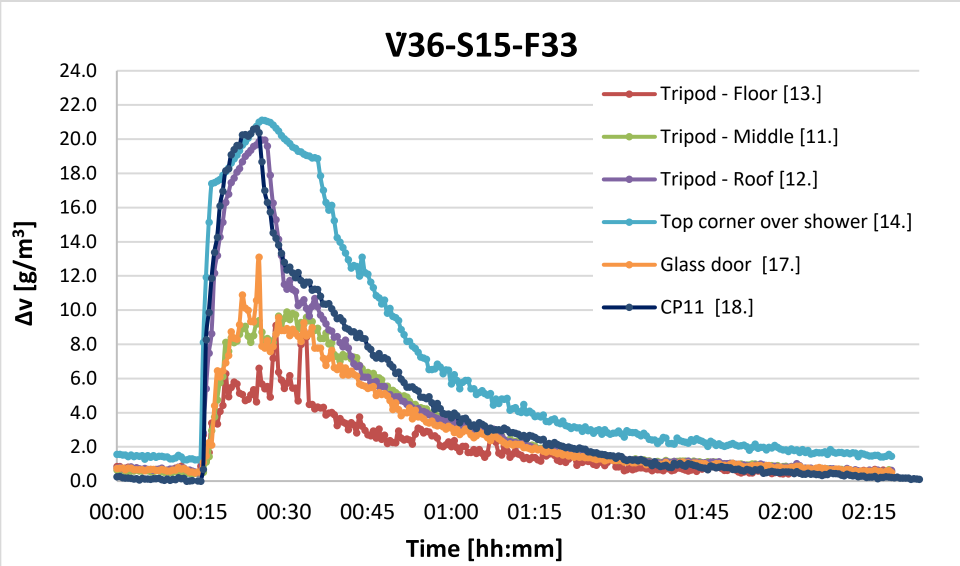

V108-S5-F30
Δv [g/m³]
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

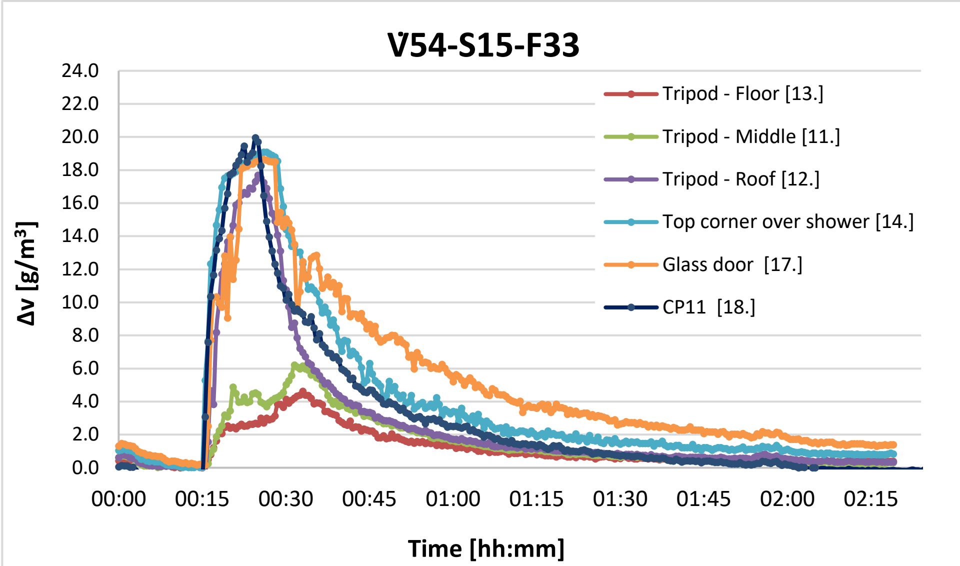

V̇36-S15-F30
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

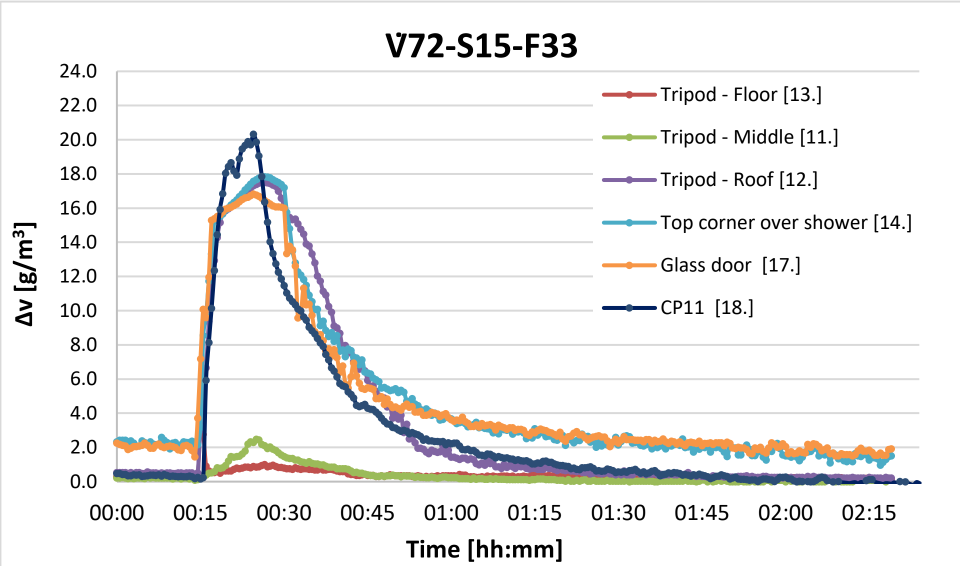

V̇54-S15-F30
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

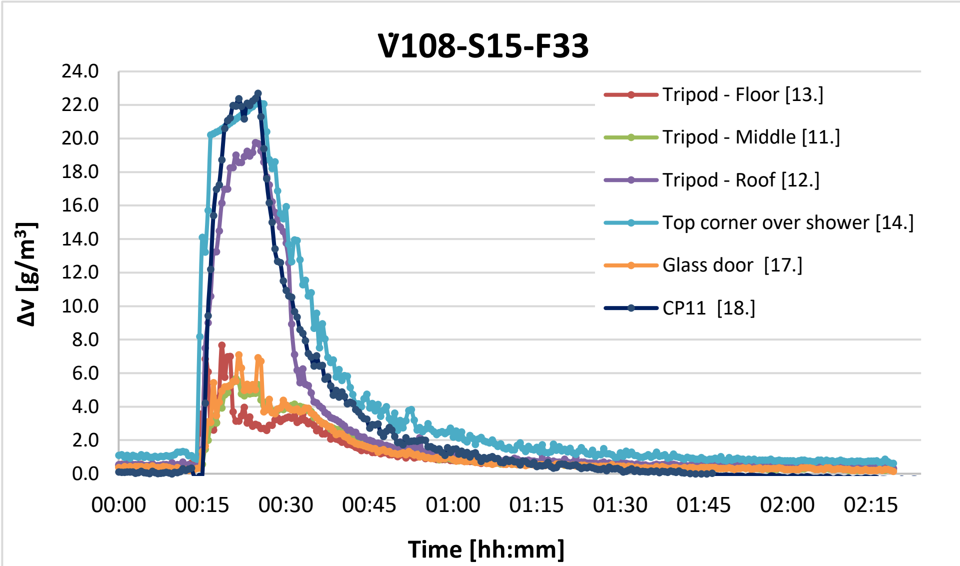

V̇72-S15-F30
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

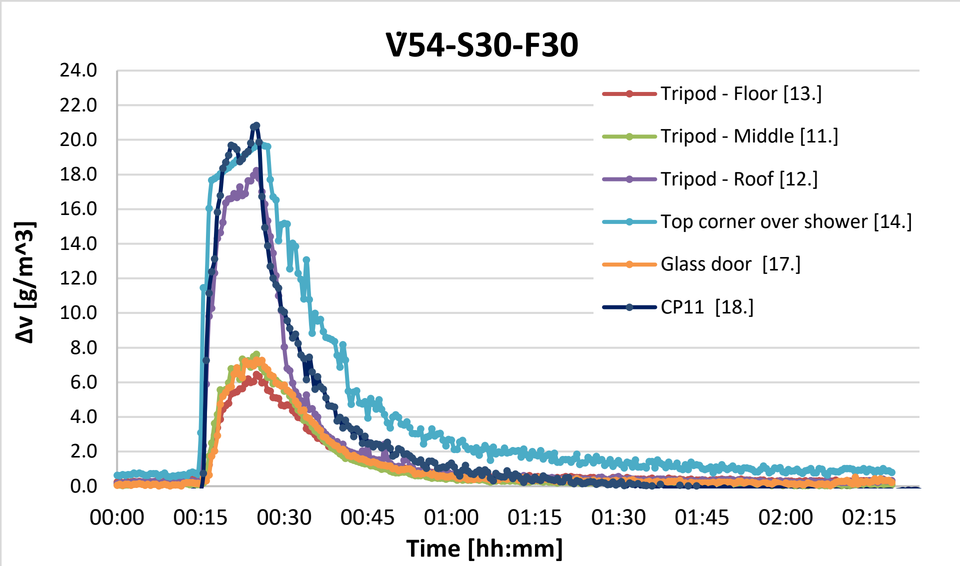

V̇108-S15-F30
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

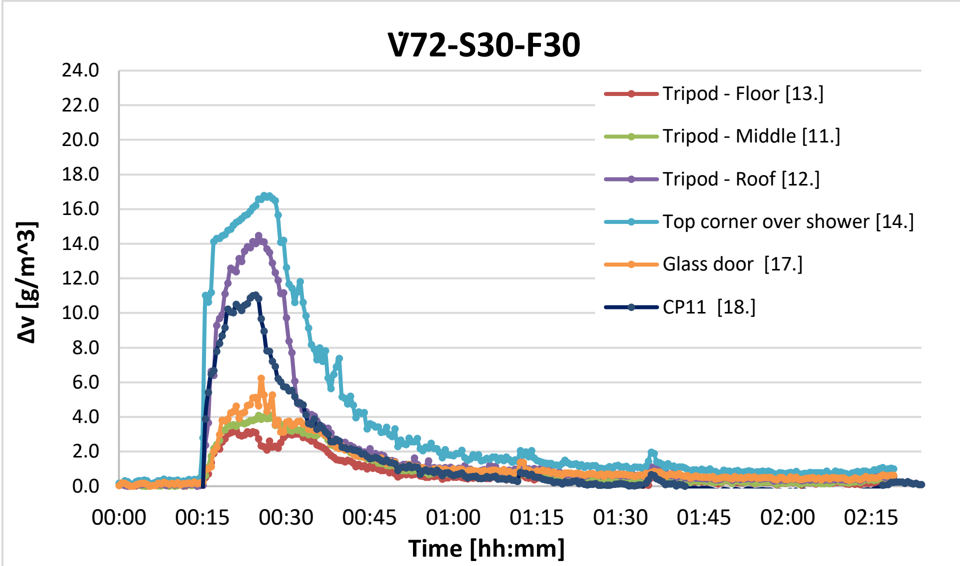

V36-S15-F33
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]


V54-S15-F33
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

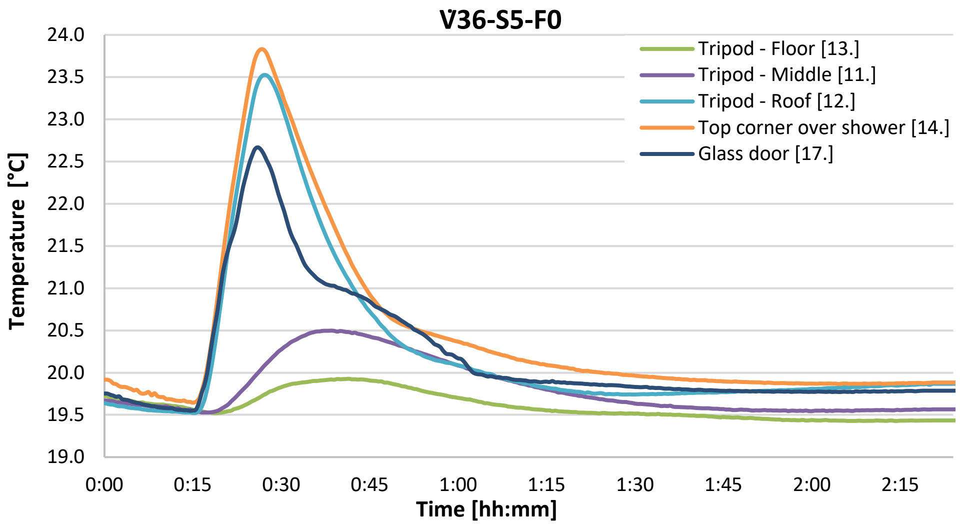

V72-S15-F33
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

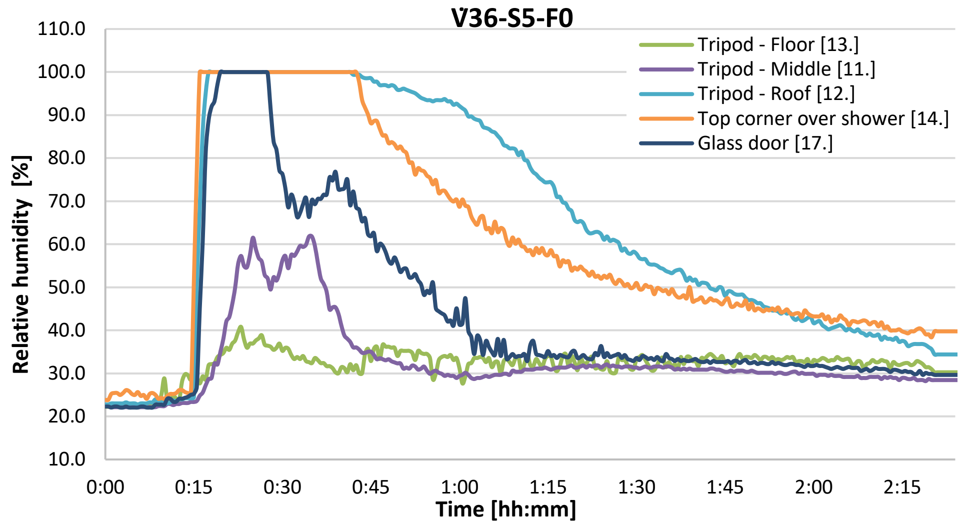

V108-S15-F33
Δv [g/m³]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]

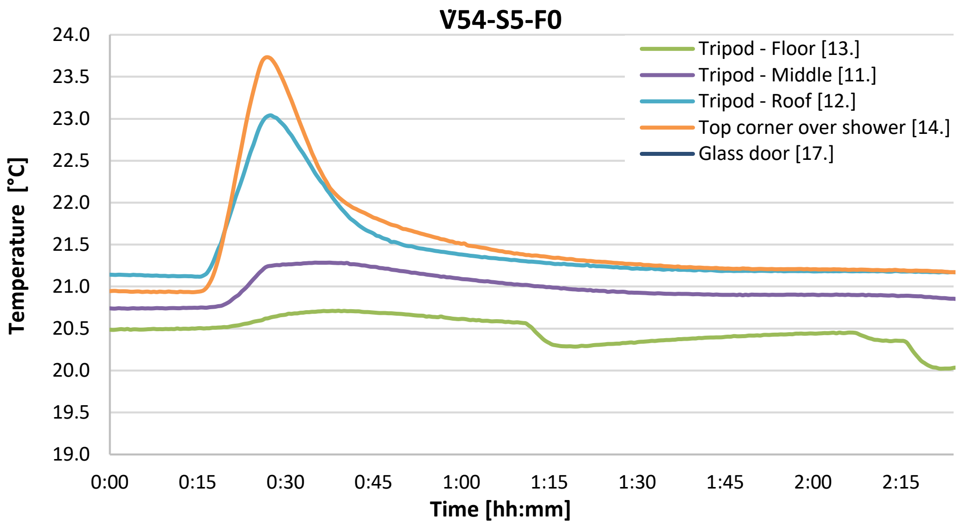

V54-S30-F30
Δv [g/m^3]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15

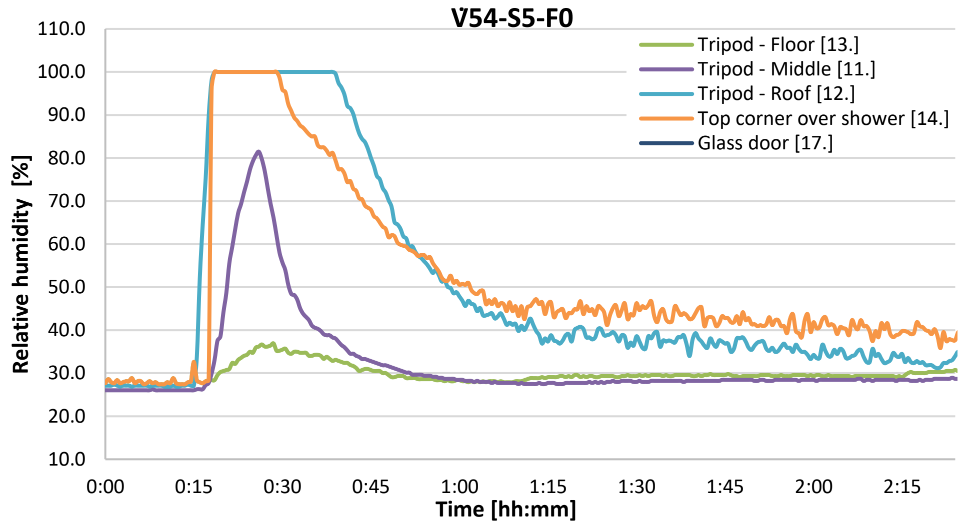

V72-S30-F30
Δv [g/m^3]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
CP11 [18.]
24.0
22.0
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:15

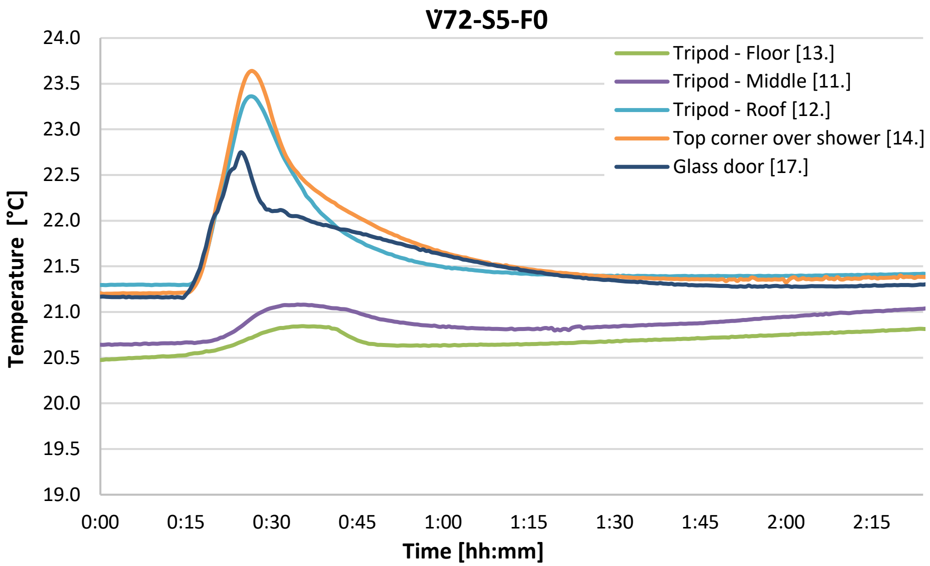
M – Spatial results

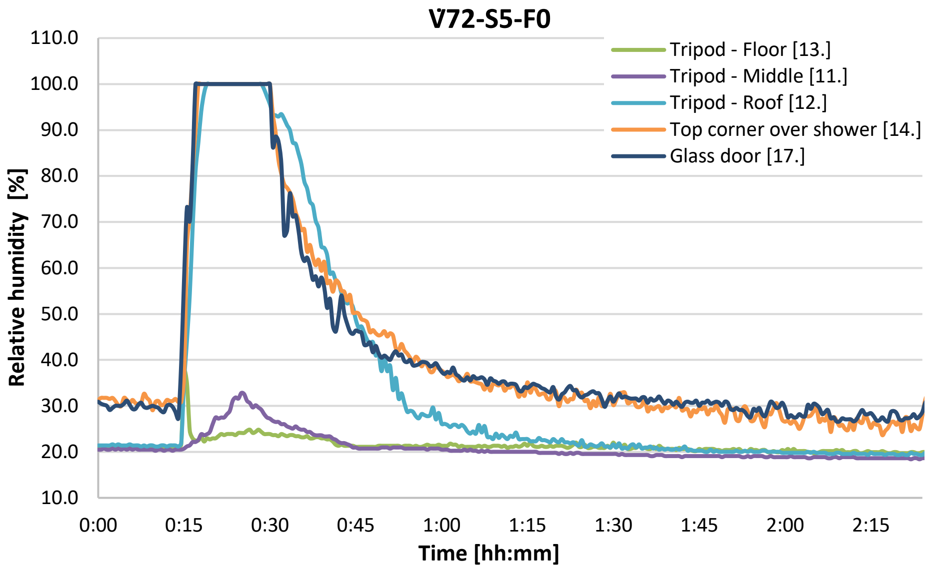


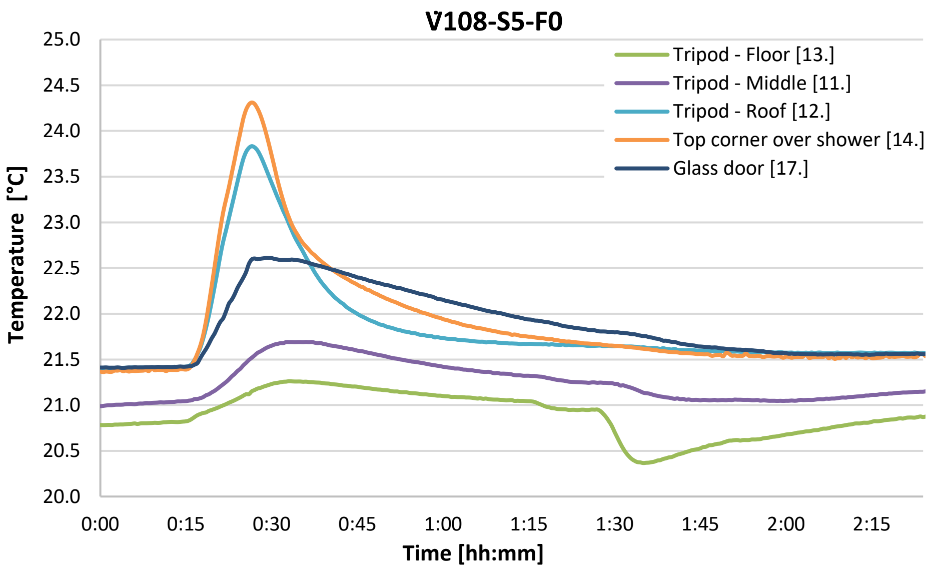


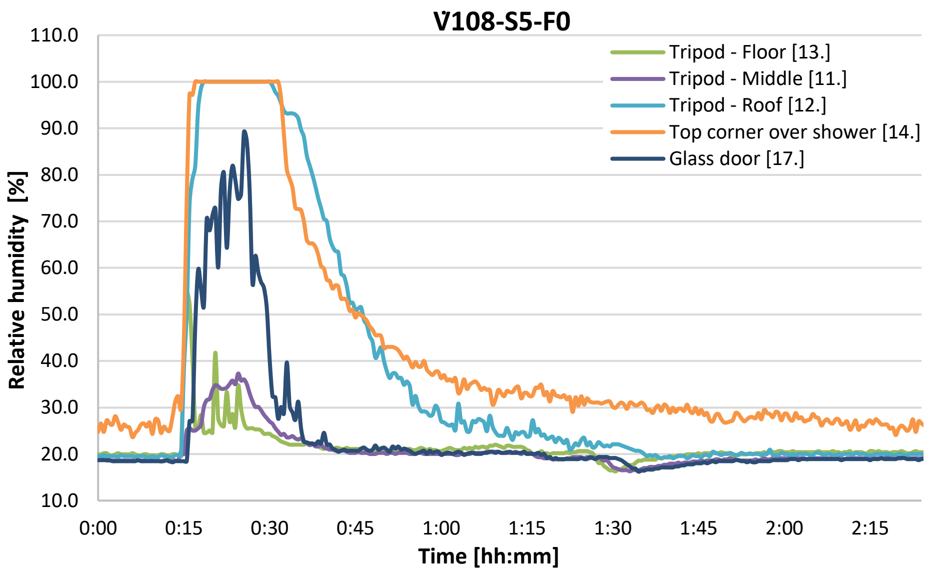


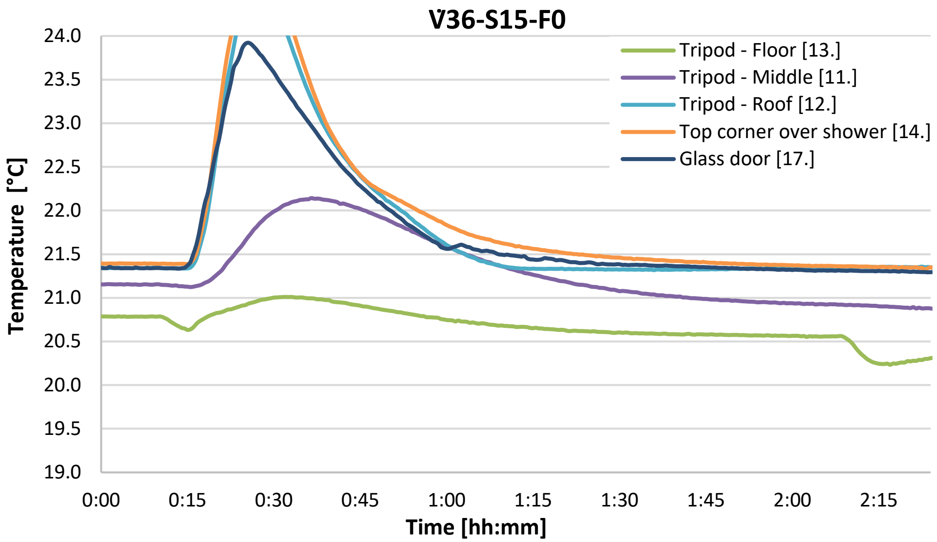



V72-S5-F0
Temperature [°C]
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
19.5
19.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

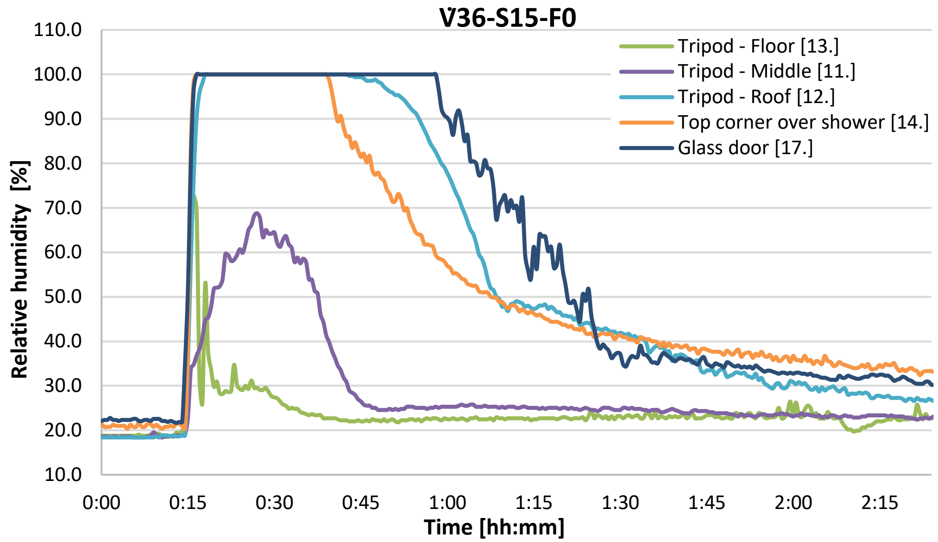

V72-S5-F0
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]


V108-S5-F0
Temperature [°C]
25.0
24.5
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

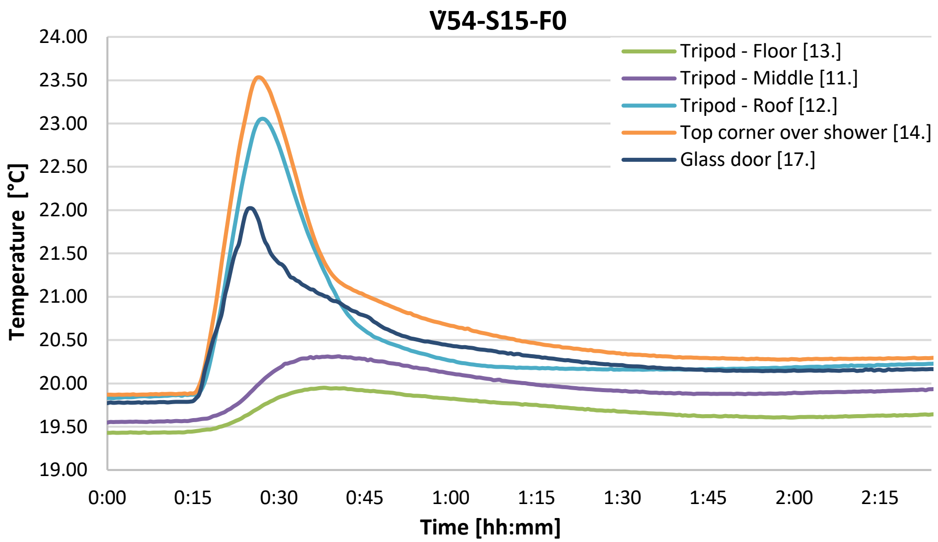

V108-S5-F0
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]



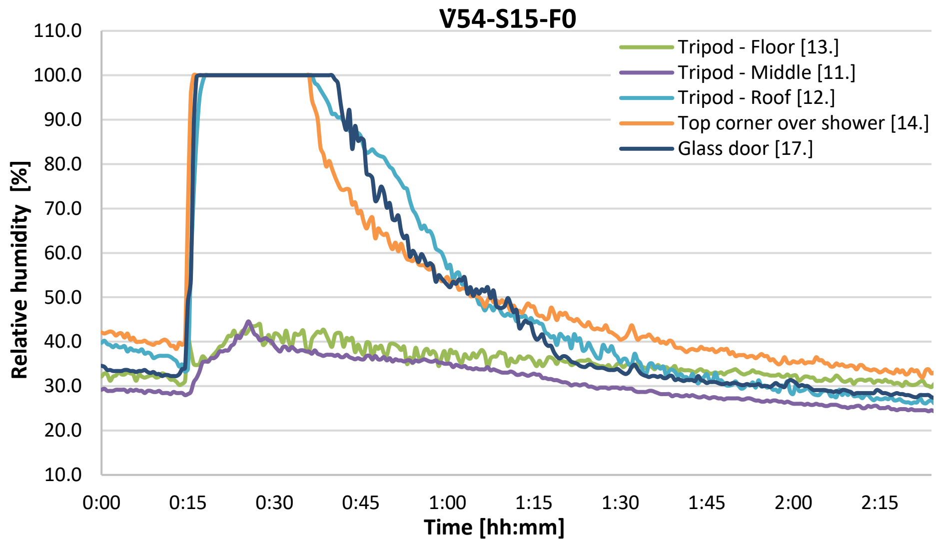
V36-S15-F0
Temperature [°C]
24.0
23.5
23.0
22.5
22.0
21.5
21.0
20.5
20.0
19.5
19.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]



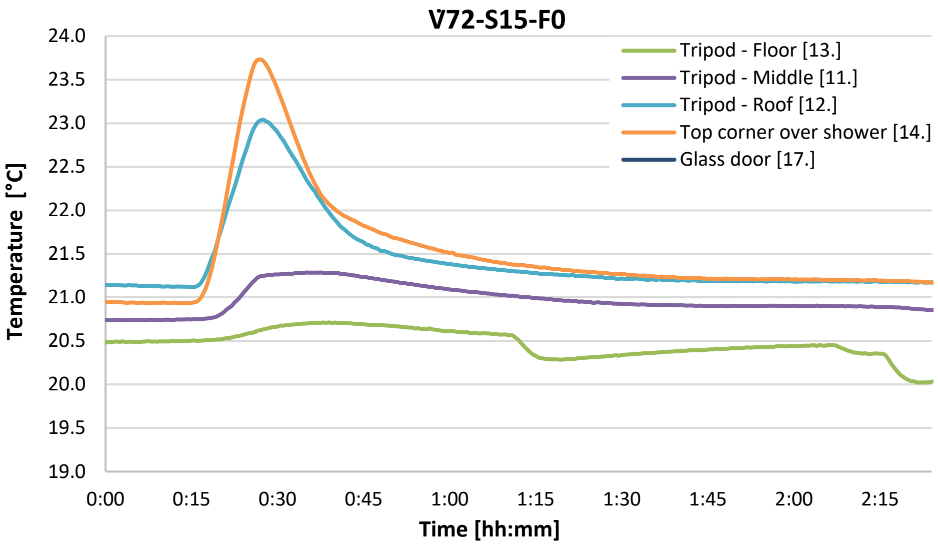
V36-S15-F0
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

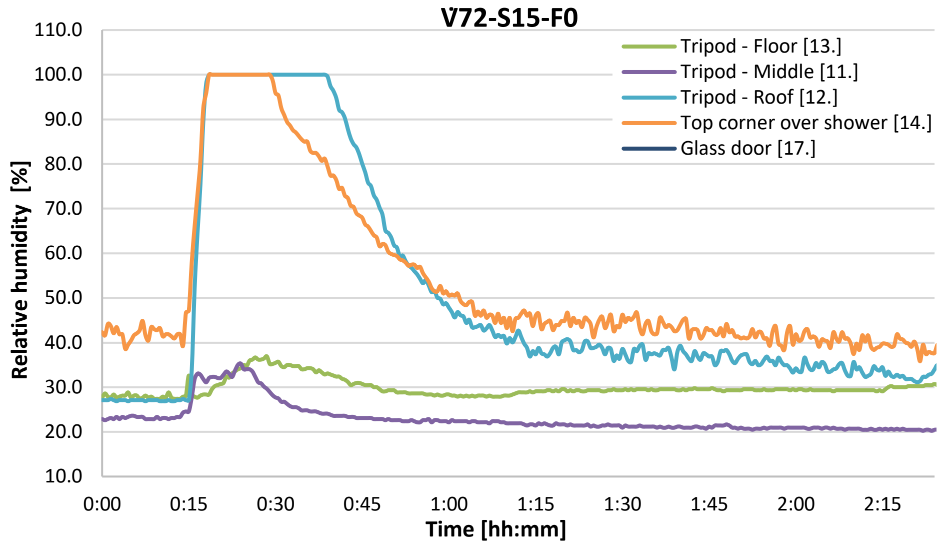


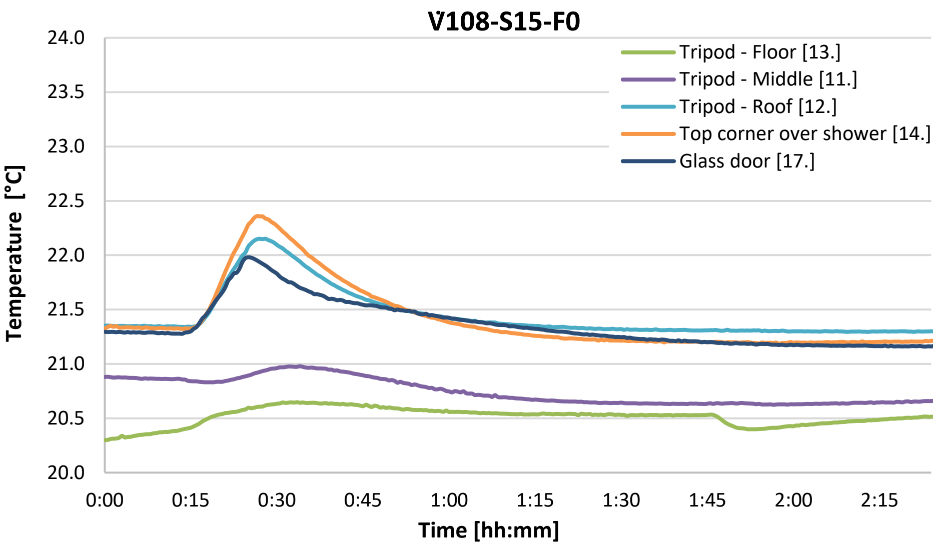
V54-S15-F0
Temperature [°C]
24.00
23.50
23.00
22.50
22.00
21.50
21.00
20.50
20.00
19.50
19.00
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

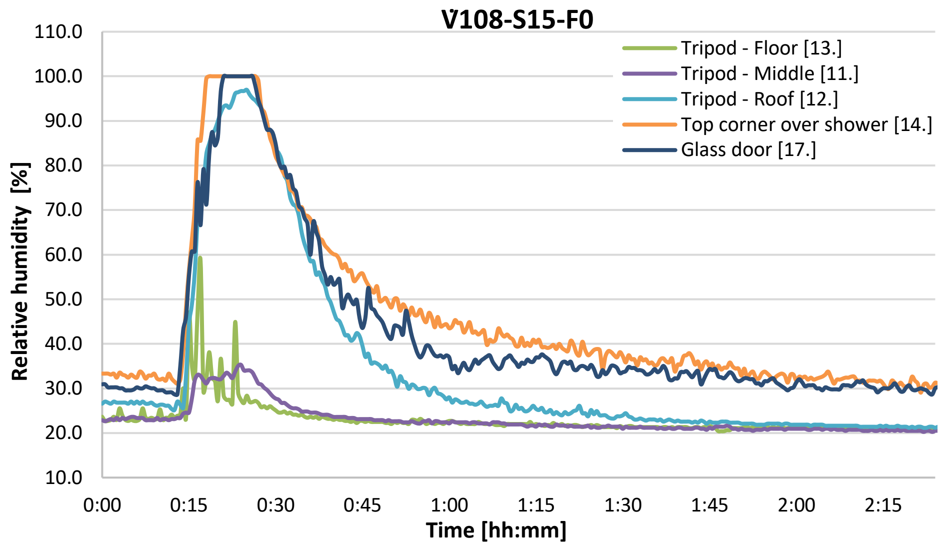


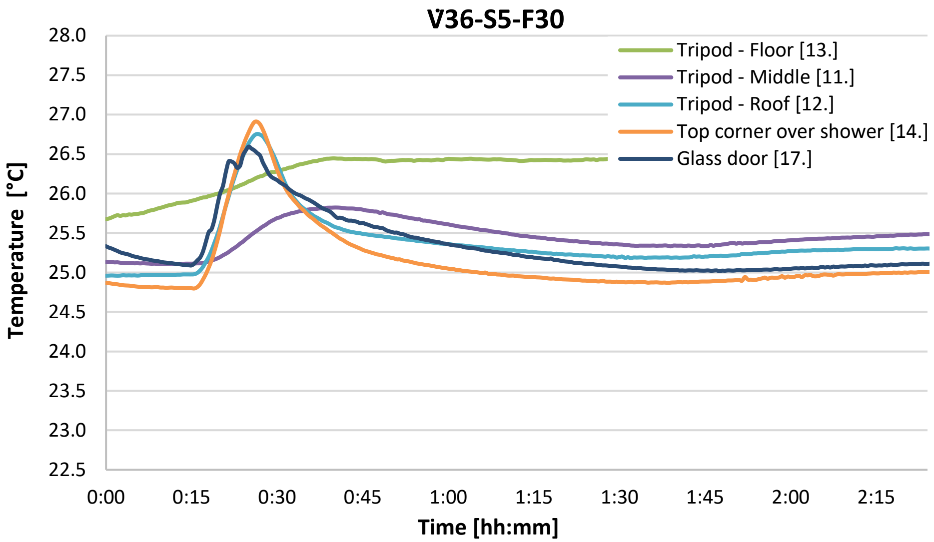
V54-S15-F0
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

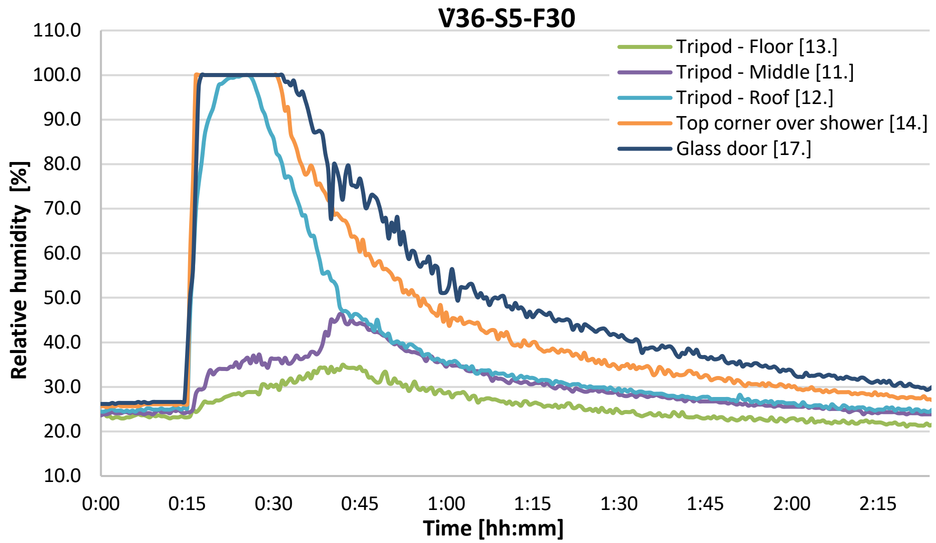

V̇72-S15-F0
Temperature [°C]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

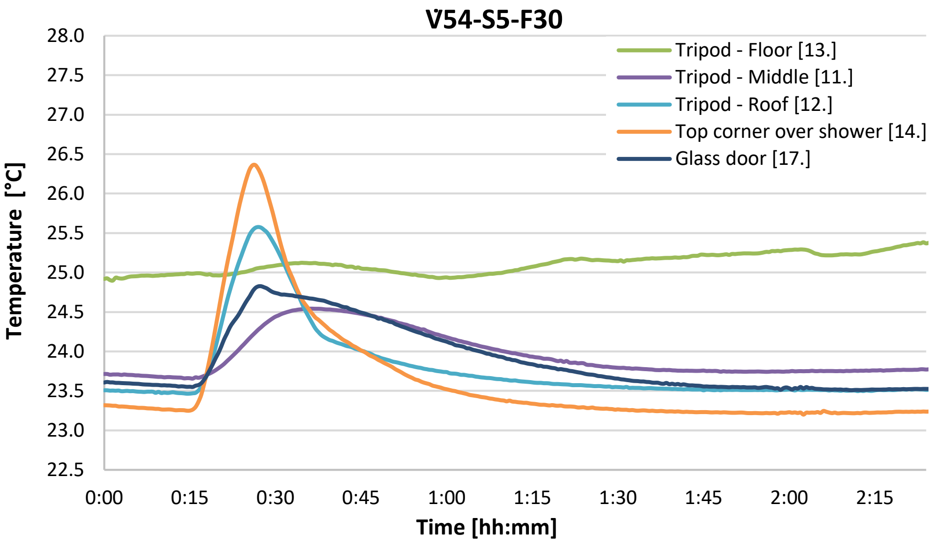

V̇72-S15-F0
Relative humidity [%]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

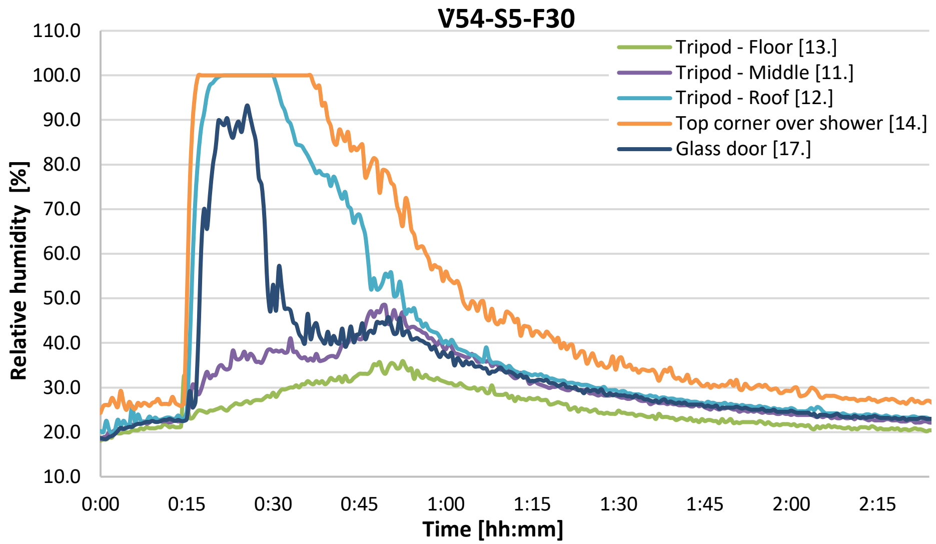

V̇108-S15-F0
Temperature [°C]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

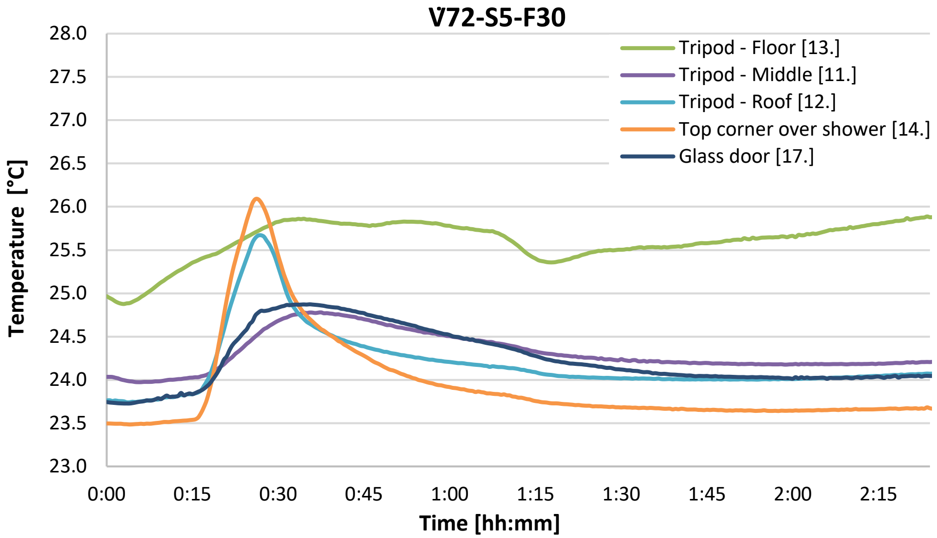

V̇108-S15-F0
Relative humidity [%]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

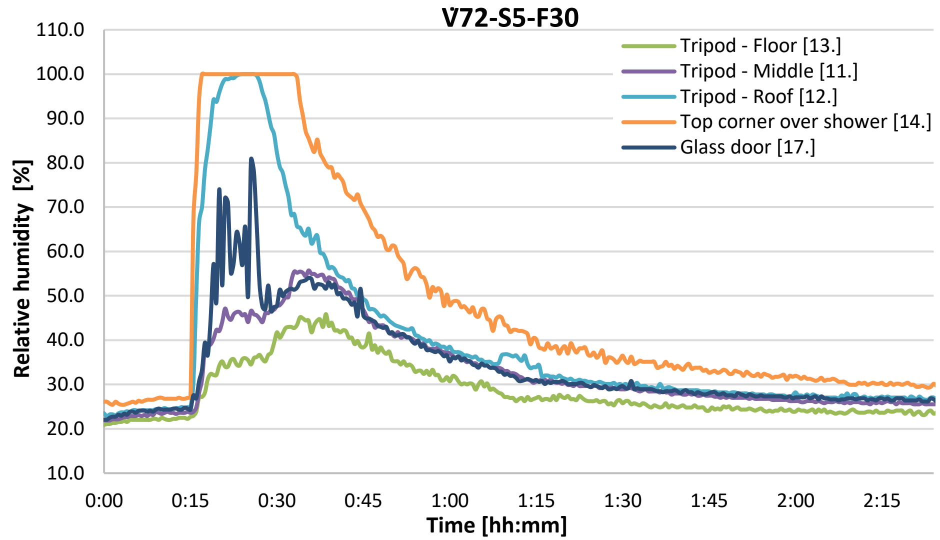

V36-S5-F30
Temperature [°C]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

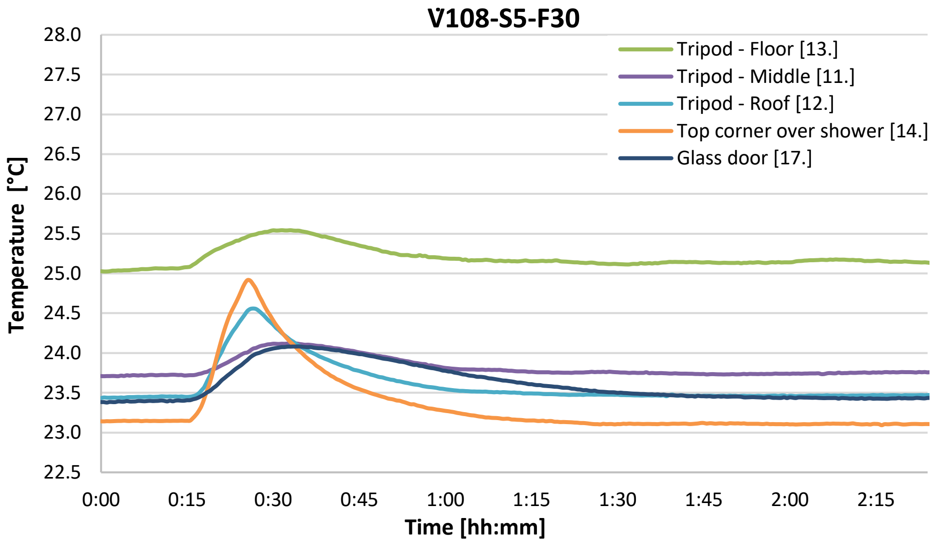

V36-S5-F30
Relative humidity [%]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

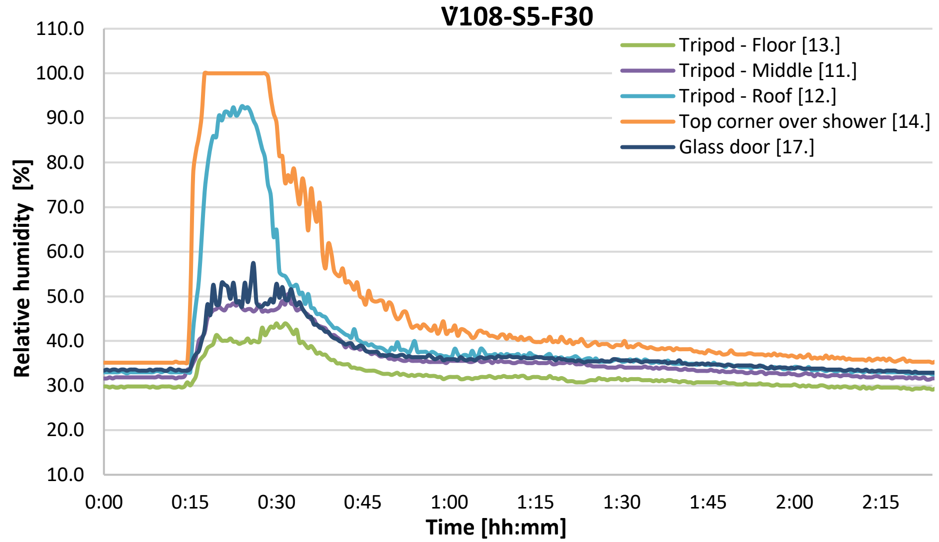

V54-S5-F30
Temperature [°C]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

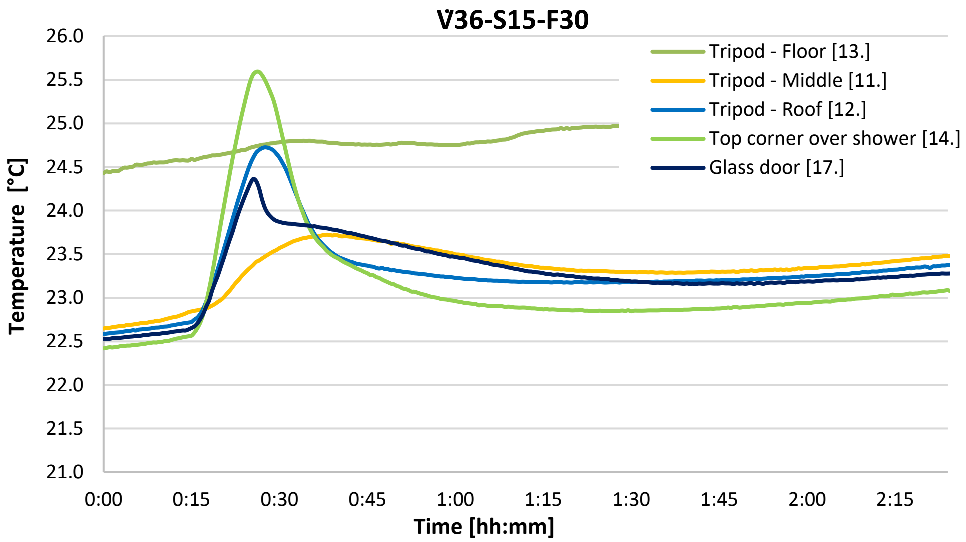

V54-S5-F30
Relative humidity [%]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]

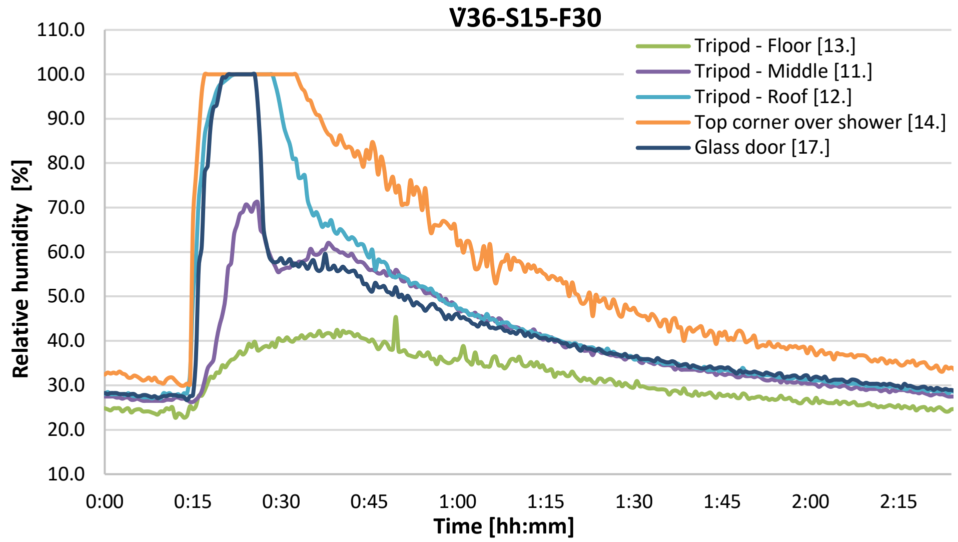

V72-S5-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
Time [hh:mm]

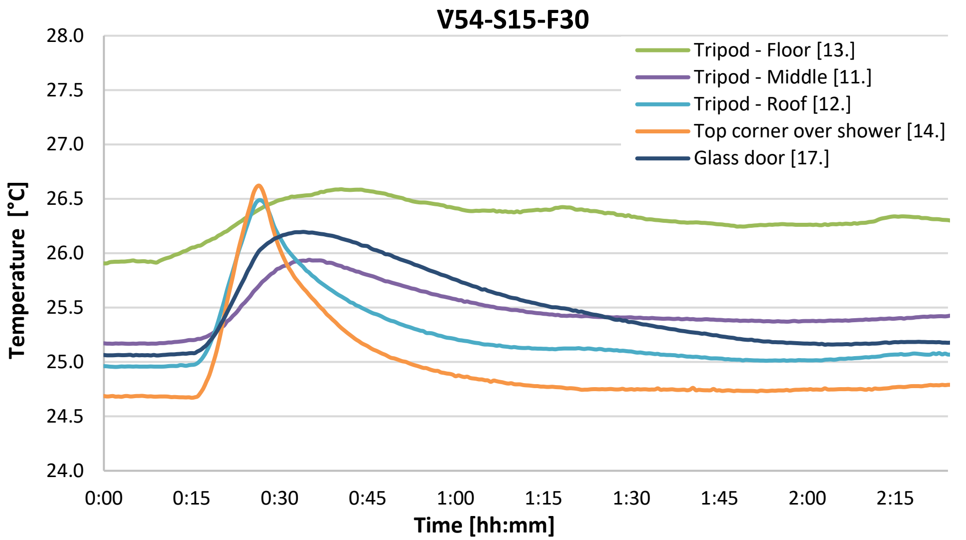

V72-S5-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
Time [hh:mm]

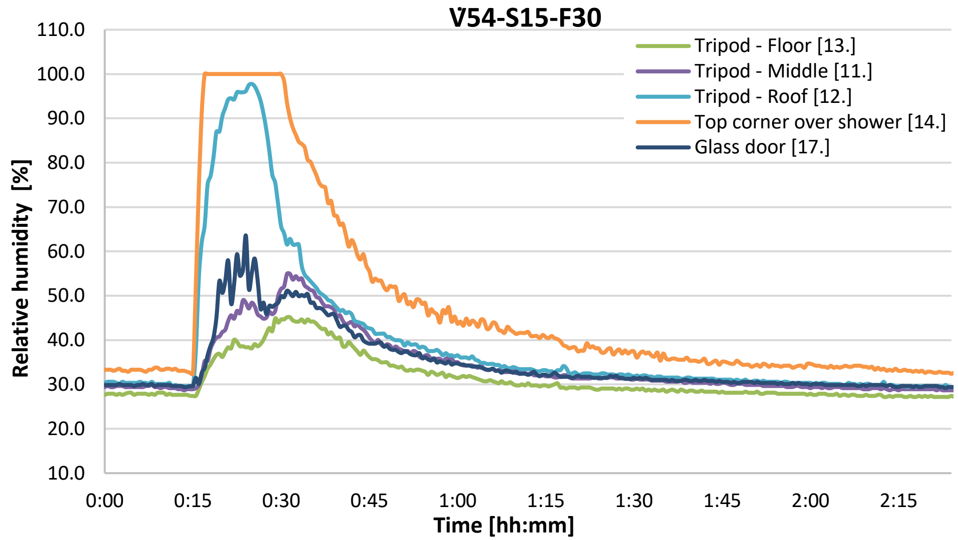

V108-S5-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
Time [hh:mm]

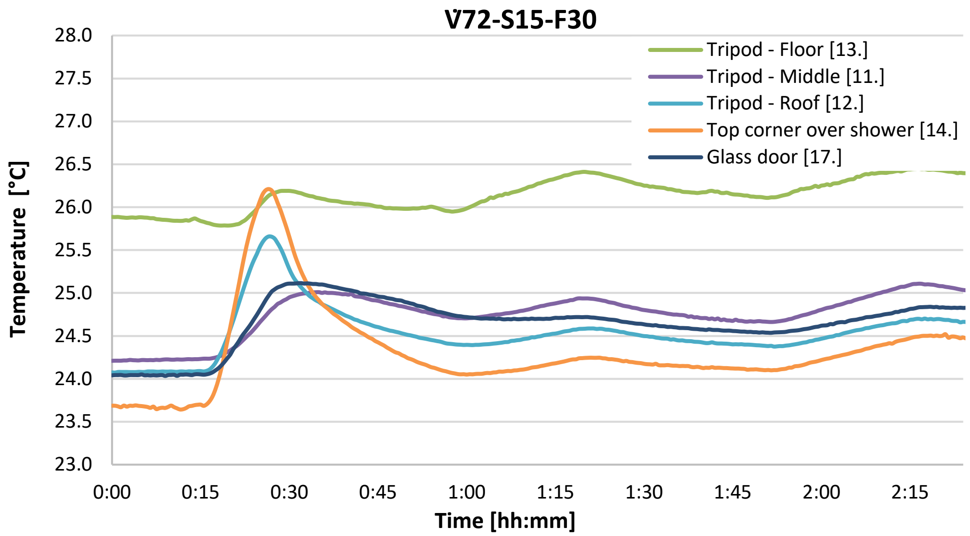

V108-S5-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
Time [hh:mm]

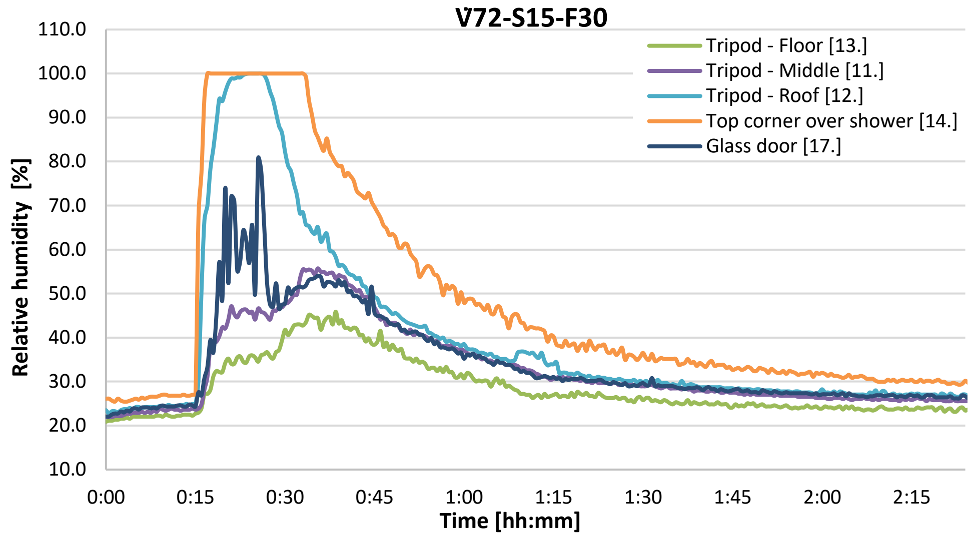

V36-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
Time [hh:mm]

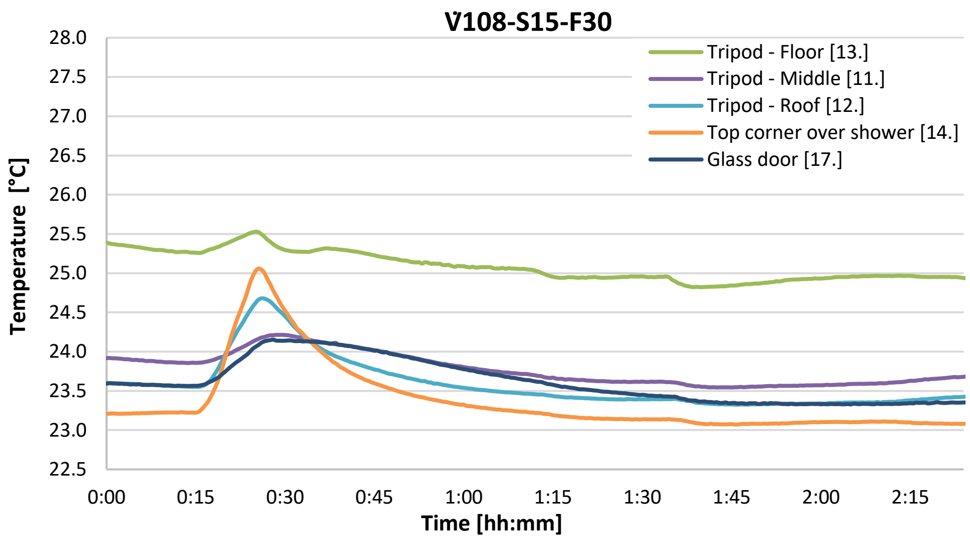

V36-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
Time [hh:mm]

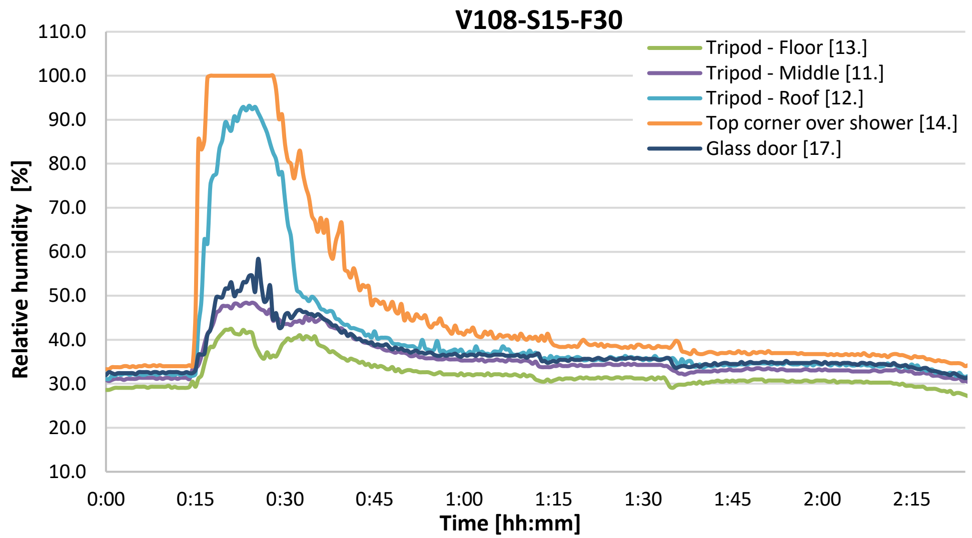

V54-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
Time [hh:mm]

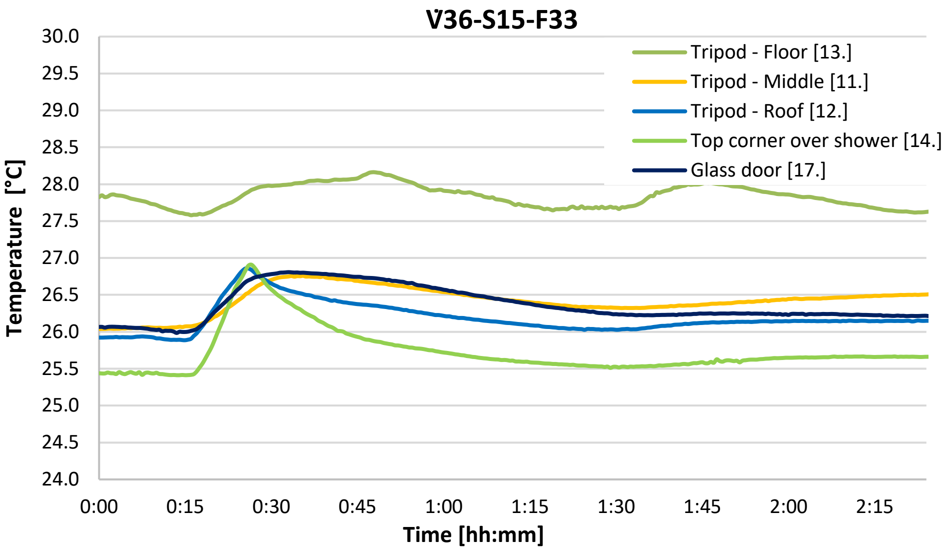

V54-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
Time [hh:mm]

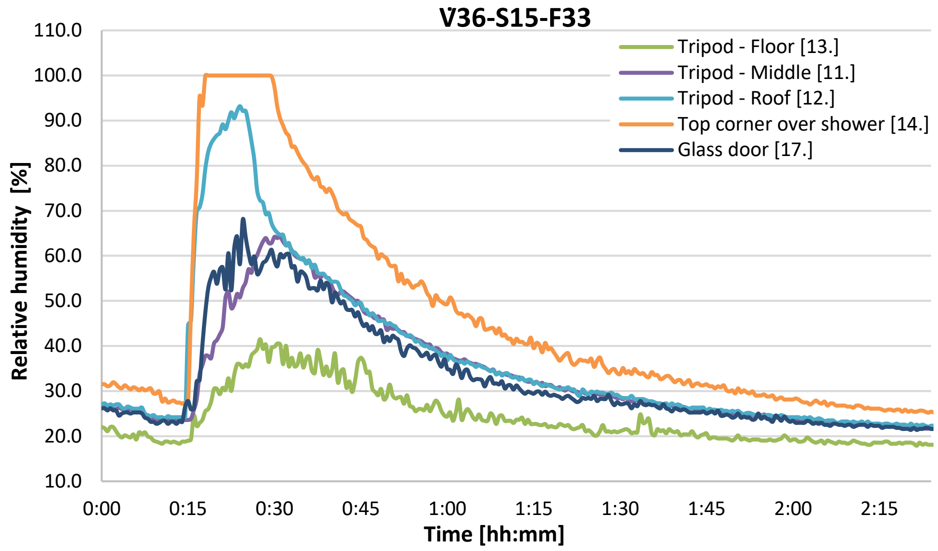

V72-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
28.0
27.5
27.0
26.5
26.0
25.5
25.0
24.5
24.0
23.5
23.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

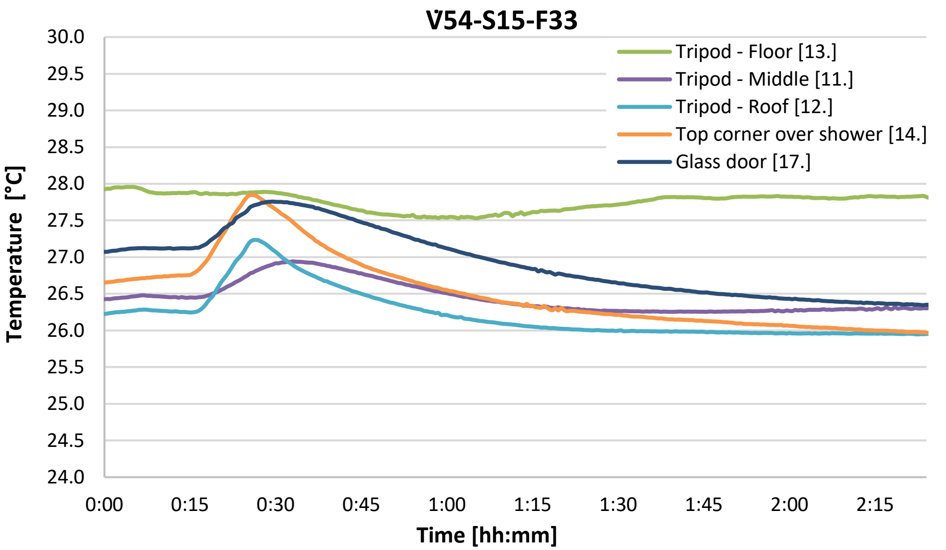

V72-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

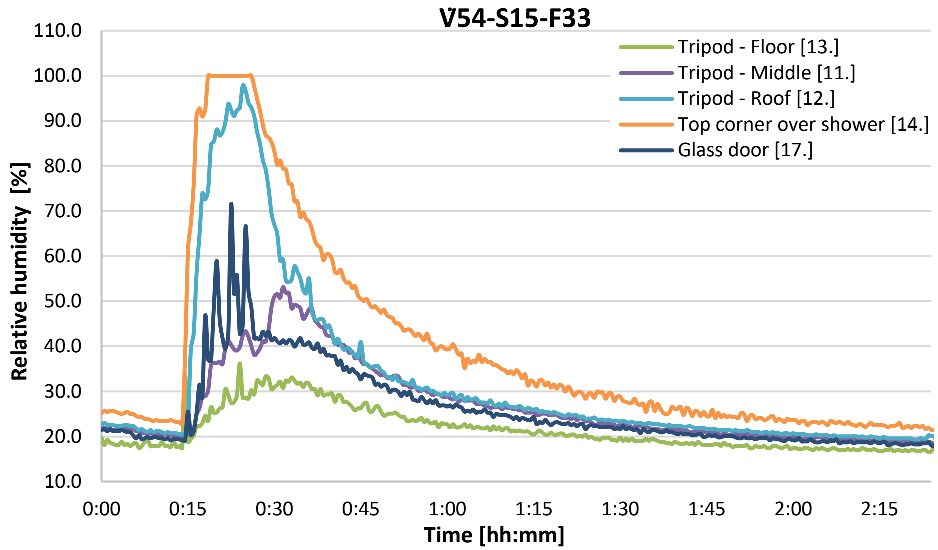

V108-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
28.0
27.5
27.0
26.5
26.0
25.5
25.0
24.5
24.0
23.5
23.0
22.5
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

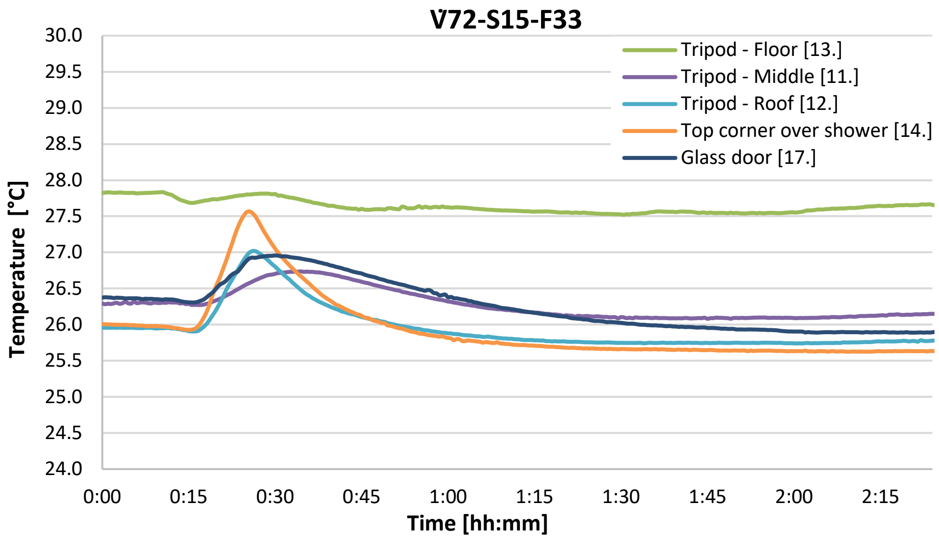

V108-S15-F30
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

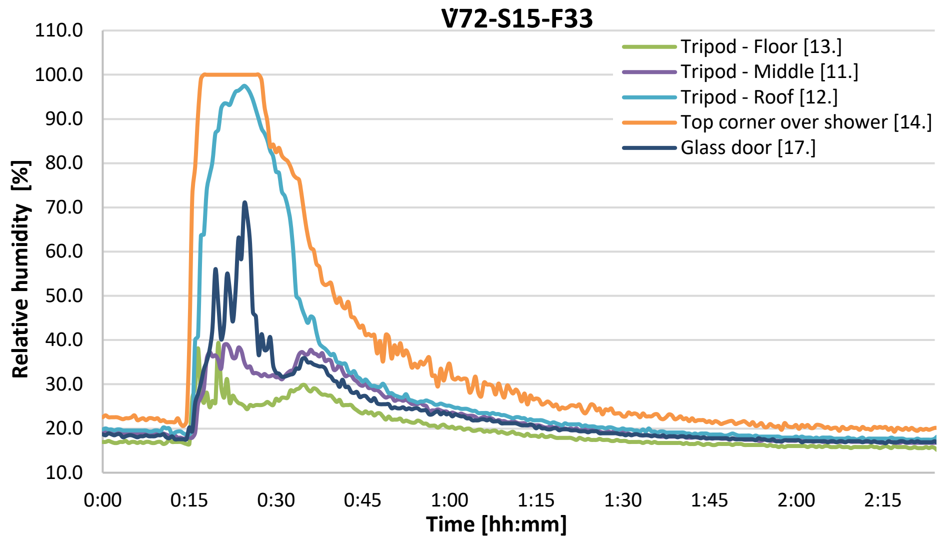

V36-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
30.0
29.5
29.0
28.5
28.0
27.5
27.0
26.5
26.0
25.5
25.0
24.5
24.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

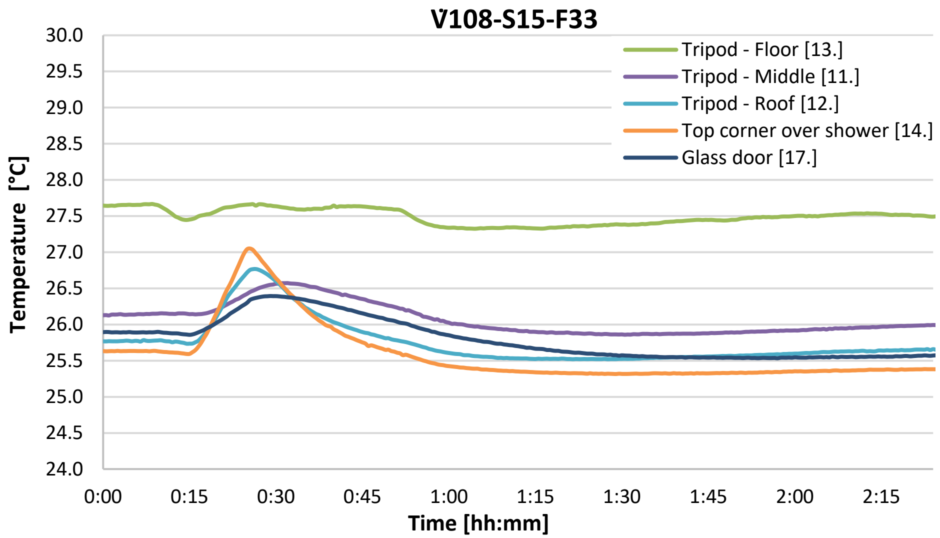

V36-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

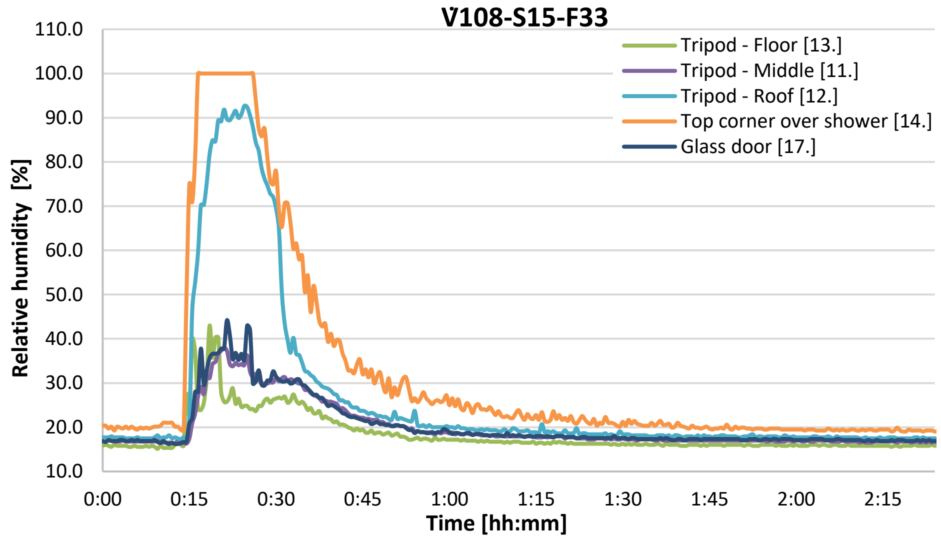

V54-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
30.0
29.5
29.0
28.5
28.0
27.5
27.0
26.5
26.0
25.5
25.0
24.5
24.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

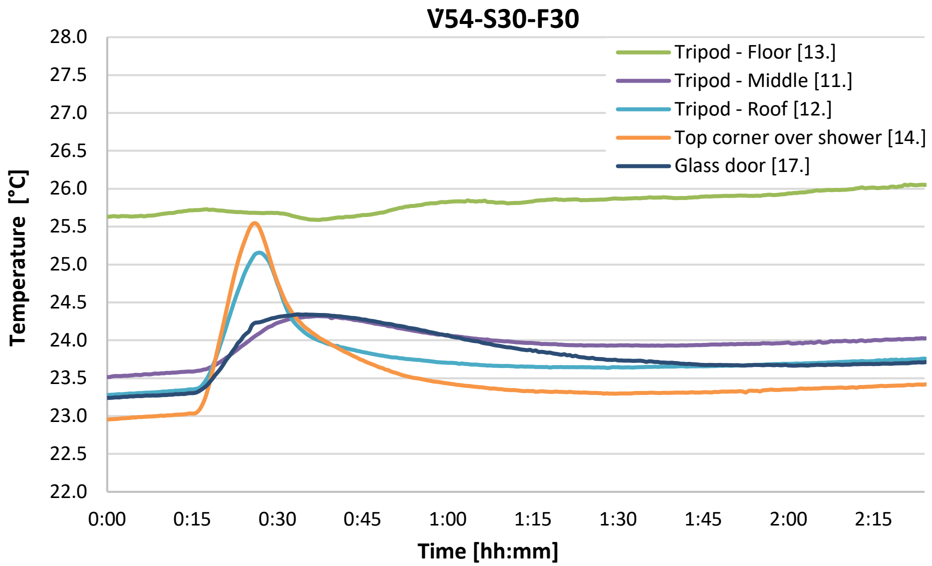

V54-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
110.0
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0:00
0:15
0:30
0:45
1:00
1:15
1:30
1:45
2:00
2:15
Time [hh:mm]

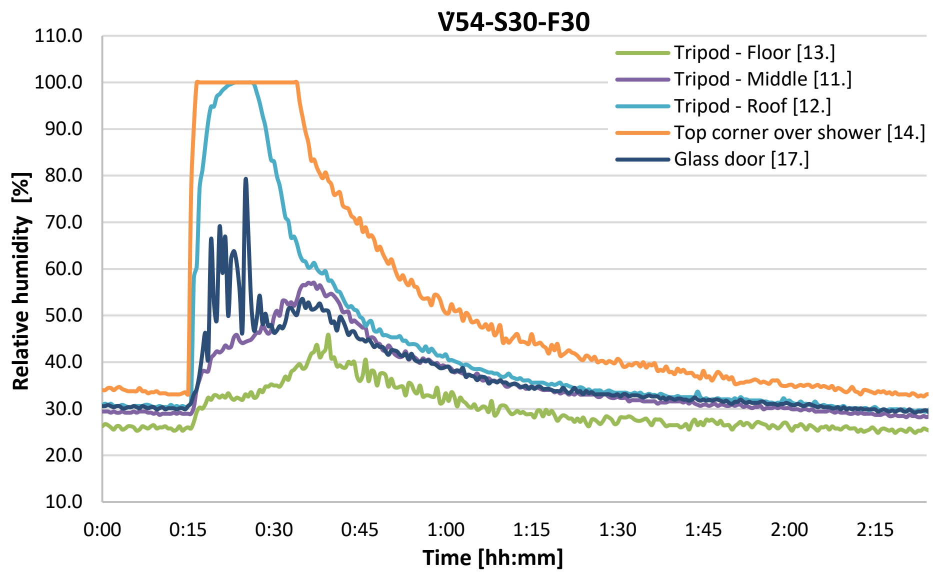

V72-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
Time [hh:mm]

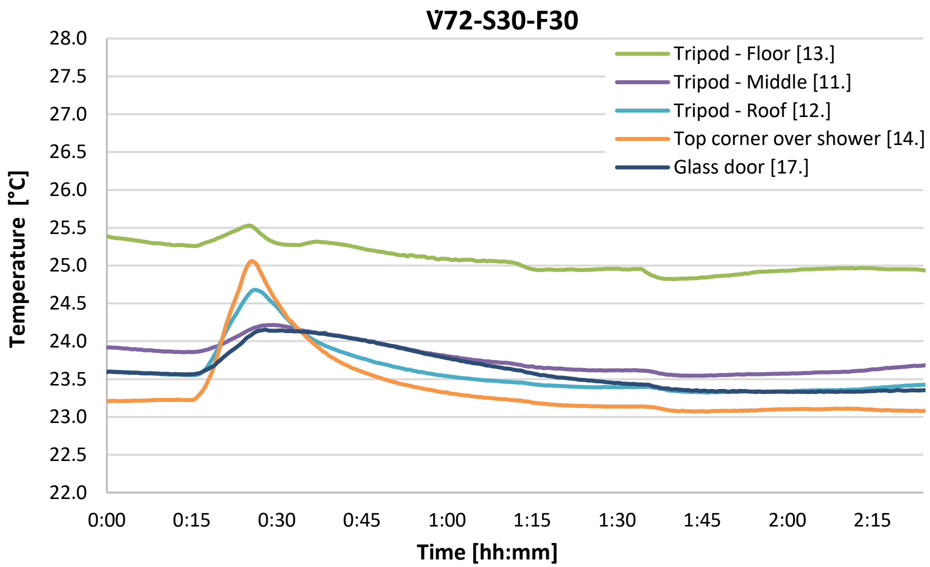

V72-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
Time [hh:mm]

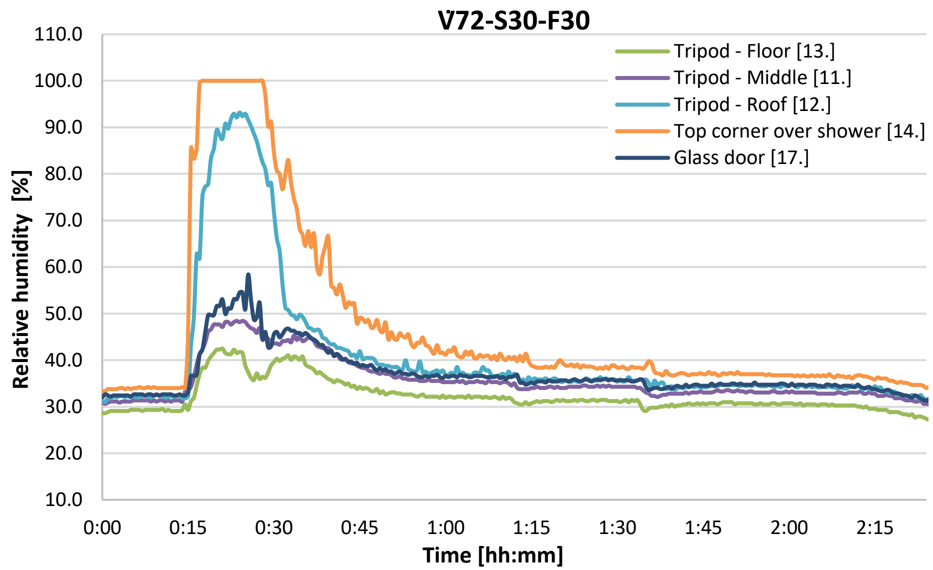

V108-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Temperature [°C]
Time [hh:mm]


V108-S15-F33
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]
Relative humidity [%]
Time [hh:mm]


V54-S30-F30
Temperature [°C]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]


V54-S30-F30
Relative humidity [%]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]


V72-S30-F30
Temperature [°C]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]


V72-S30-F30
Relative humidity [%]
Time [hh:mm]
Tripod - Floor [13.]
Tripod - Middle [11.]
Tripod - Roof [12.]
Top corner over shower [14.]
Glass door [17.]