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Cloth-Water Interaction for Air Humidification in HDH Desalination

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CLOTH-WATER INTERACTION FOR AIR HUMIDIFICATION IN HDH DESALINATION

A Thesis

by

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ABSTRACT

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The humidification-dehumidification (HDH) desalination technology is a promising desalination process that has the potential to provide cost-effective and environmentally friendly saltwater desalination, especially when combined with renewable energy sources. The working principle mimics the natural hydrologic cycle, involving the evaporation of seawater into water vapor (humidification) and condensation into freshwater (dehumidification). HDH desalination can be land-based or ocean-based. Some of the advantages of ocean-based systems include removing pretreatment processes, utilization of ocean energy (i.e. thermal and kinetic), and eliminating brine production. This study focuses on the design and experimental testing of a novel humidifier device using parallel layers of clothing fabric for ocean based HDH desalination. For a practical and cost-effective humidifier design, only commercially available fabric materials are considered for this study. A total of 38 fabrics are tested to characterize their water retention and capillary wicking attributes. The relation of these fabric properties to the heat and mass transfer performance of the humidifier are discussed. It is found that a balance between the water retention and wicking performance of the fabric, is crucial to improve the efficiency of the humidifier.

DEDICATION

I dedicate this work to all the persons that helped me during all my degree process. Some individuals offered their kindness in different ways. I dedicate this to my family, who gave the structure of living that propitiated my development and capacity to focus on my studies. I appreciate Rafael Garcia for listening to my ideas and thoughts for long times and helped me process and understand part of my research information. I feel a huge gratitude towards Ada Duran for offering me a hand when I needed it. My scholar friend Miroslava is always giving me the little push to do what I do not dare to do, so I dedicate this work to her as well. They are three parts of my support network, but the rest are also appreciated for their help.

I also dedicate this work to those passionate to learn students that I have ever met, and my university friends back in Mexico who wanted an opportunity like mine. I recognize the arbitrariness of my luck, but I also recognize the effort that I put into it, that I did not waste the opportunities that have come in my way.

And I want to thank myself for taking care of me and making some of the most important decisions I have ever done in my life. For sure, this process involved little changes that over time I can see reflected the results in a better health and quality of life, and I hope for a better living for all of us.

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CHAPTER I

INTRODUCTION

1.1 Motivation

Freshwater is a limited resource that is crucial to maintain life on Earth. Humans, flora, fauna, and the ecosystems of the entire planet are founded on this resource, but less than 1% of the surface-water is freshwater (Suring, 2020). Many regions of the world struggle with the lack of this resource. It is estimated that by the year 2050, it will be necessary to have three times the resources of planet Earth to cover the necessities of nine billion of people. However, it is not necessary to look at future predictions to witness severe water scarcity. Currently, in countries like Bangladesh (Hussam, 2013) population is in risk of being poisoned by contaminated groundwater used for human consumption (Atkinson, 2020). The number of developing countries that face serious freshwater shortages is increasing, and in first-world countries like the US, the groundwater is becoming blackish. Overall, it is estimated that around 41% of Earth's population live in areas that are water-stressed (Service, 2006). In contrast to the increasing freshwater scarcity, 97% of the world's water is ocean salt water. Therefore, cost-effective, and environmentally friendly seawater desalination has been studied as a potential solution to alleviate the freshwater crisis.

Large-scale desalination plants largely depend on traditional fossil fuel energy sources, causing a negative impact to the environment (Zhang & Xie, 2019). Because 40% of the world population lives near the coast (United Nations, 2017), and due to the energy consumption of pumping water for transporting can be as high as that of the desalination process itself (Zarzo & Prats, 2018), most of the desalination plants are concentrated in the coastal cities (Zhang & Xie, 2019).

1.2 Background

Reverse Osmosis (RO) is the most well established and energy efficient technology for the removal of salts and contaminants for freshwater production. RO is a membrane-based desalination technology. This technology works by the application of hydraulic pressure on a concentrated solution to make it pass through a water permeable membrane and filter out the salt content. In terms of energy consumption, typical seawater reverse osmosis desalination can consume as low as 2.54 kWh/m3 and as high as 4.0 kWh/m3, which compared to the 1.1 kWh/m3 of the thermodynamic limit with a practical recovery range of 50%, the state-of-the-art RO technology is approaching the maximum efficiency limits (Qasim et al., 2019). Even so, RO consumes more energy than traditional surface-water treatments of lakes and rivers (Eke et al., 2020). Unfortunately, this method has two major drawbacks. One is the disposal of high salt content brine to the oceans, which harms the coastal environment and marine species. The other is the emission of air pollutants due to the high consumption of non-renewable energy sources (Elsaid et al., 2020). Implementation of RO with renewable energy sources becomes difficult because the system demands a constant energy supply. Therefore, other desalination mechanisms must be explored to reduce the negative environmental impacts of seawater desalination.

The other major classification for desalination is the thermal-based. These systems depend on evaporation to separate the salt content from the seawater. Multistage Flash Distillation (MFD) works by the sudden reduction of pressure in a flashing chamber to make the seawater boil, and it’s one of the most well-established technologies of this classification along with Multi-effect Distillation (MED), which also operates at elevated temperatures to reach the water boiling point. These technologies are classified as high temperature. They cause more severe damage to the environment than RO due to the brine disposed into the ocean at higher temperatures. Additionally, these large-scale approaches are classified as extensive energy consumption (Elsaid et al., 2020) and capital-intensive methods, leading to high capital investment costs, and to high overall desalination costs (Eke et al., 2020).

Other technologies use electrical energy to induce sweater desalination. Examples include: Capacitive Deionization (CDI), Electrodialysis, and Electrodialysis. CDI, however, has been proven to require a high power consumption and have low thermodynamic efficiency (Oren, 2008). Other methods that have been studied include: Adsorption Desalination (AD), Forward Osmosis (FO), Membrane Distillation (MD), and Nuclear Desalination. AD requires adsorbent materials on the evaporation unit to collect the water particles. Various AD systems combined with other desalination technologies have been proposed in literature (Ng et al., 2013). Forward Osmosis (FO) depends on draw solutions to achieve higher osmotic pressure. Standalone FO requires more energy than RO, but it can be a feasible option in a hybrid system (Akther et al., 2015). Membrane Distillation (MD) utilizes a membrane to permeate water vapor coming from boiling seawater and condensate it at the other side of the membrane, so it works by a membrane and by thermal energy (Alkhudhiri et al., 2012).

Hybrid systems can take advantage of an effect of a main function to perform desalination as a secondary purpose, that is the case of the Nuclear Desalination, which uses the heat produced by the high density-energy nuclear reactor to provide heat for thermal desalination or to generate electricity for a membrane-based system (Al-Othman et al., 2019). Other novel approaches include fog collection for direct humidity extraction form the air. Even on low humidity environments such as deserts, freshwater can be extracted from the air (Fathieh et al., 2018). Emerging desalination technologies that are powered by renewable energy sources are mostly in the development stage.

Technologies mainly powered by renewal energies typically employ solar energy. Solar Stills systems are powered by thermal solar energy, and they use the sun rays to evaporate seawater inside a basin and collect the condensed freshwater on the transparent cover. Extensive research has been done in literature; the incorporation of phase change materials, basin fins, and nanoparticles are likely to enhance the freshwater production (Srithar & Rajaseenivasan, 2018).

A similar technology is the humidification-dehumidification (HDH) desalination. The working principle of the HDH Desalination mimics the natural hydrologic cycle, which involves evaporation of seawater into water vapor and condensation of the vapor to produce freshwater. The HDH technology benefits from the ability of the air to carry water molecules and the psychrometric properties of air that allows it to increase its water vapor carrying capability at higher temperatures. These methods operate as a low temperature desalination system, which makes them suitable to implementation with renewal energies, and suitable for small-scale applications such as water desalination for remote areas or islands (Leijon & Boström, 2018).

1.3 Humidification Dehumidification Desalination Systems

Typical cycle configurations of an HDH are Closed-Water Open-Air (CWOA) and Open-Water Clased-Air (OWCA). They can have water heated, air heated, or both. The three basic units that constitute an HDH system are the humidifier, the dehumidifier, and the heat source. The humidifier introduces moisture into the hot dry air coming from the heat source, producing humid air at the exit. The dehumidifiers cool down the hot humid air condensing the water molecules contained and yielding freshwater. And the heat source produces thermal energy to warm up either seawater, the air, or both. The brine discharges at the humidifier and it is lower than other desalination methods. Figure 1 shows a diagram of the basic configuration of a typical HDH desalination system.

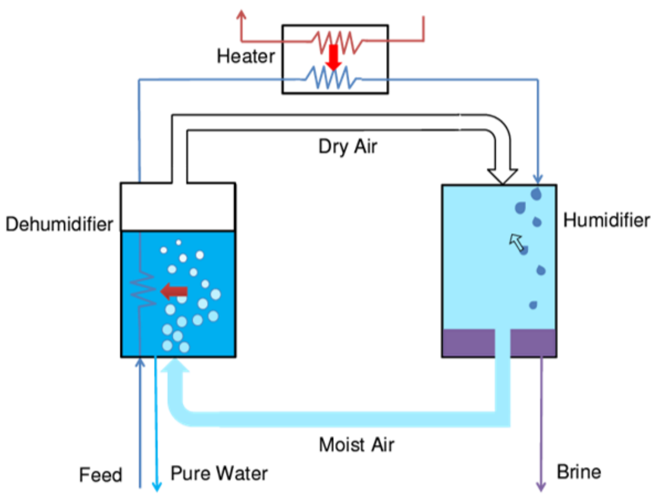

Figure 1: Concept diagram of a typical HDH Desalination System.

An important parameter of an HDH is the pressure that the system is run at. Experimental investigation has been performed in literature to determine the effects of changing this parameter. A sub-atmospheric pressure in the humidifier could benefit the production rate of freshwater (Rahimi-Ahar et al., 2018). Higher pressure on the dehumidifier can also contribute to this

(Siddiqui et al., 2017). Most of the HDH are land-based, there are very few ocean-based proposals. Some of the advantages of ocean-based systems include removing pretreatment processes, utilization of ocean energy (i.e. thermal and kinetic), and eliminating brine production.

1.4 Air Humidification Devices

Humidifier units have been proposed in literature to achieve a better overall performance. Spray humidification works with positioned pointing down nozzles inside a vertical cylinder vessel spraying water into an incoming upward air stream. Additionally, packed materials are employed to increase the heat and mass transfer area between the water and air (Dehghani et al., 2018). Bubble column is a humidification mechanism in which a sparger injects a turbulent air stream below a hot water body, making the water vapor to diffuse into bubbles that move upward until they reach the outlet as humidified warm air. Both the nozzle and the sparger create a significant pressure drop. Other methods have used Nafion membrane is used sandwiched between a gas flow channel (permeate side), and a humid gas flow channel (feed side). The water permeates through the membrane and evaporates into the gas stream due to a lower partial pressure exerted on the permeate side of the membrane (Park & Oh, 2009). A study compared the evaporation rate between a wetted surface and a free water surface. It is concluded that at a low wind velocity the rate of evaporation on the wetted surface is the highest, and the result is completely inverse when the wind velocity is high (Tang & Etzion, 2004). (Tariq et al.). Computer Fluids Dynamics (CFD) has allowed the study of other concepts like the combination of humidification and dehumidification in one single enclosure for dewater desalination (Saeed et al., 2016), (Kassim et al., 2011). Having a system with two walls, one hot and the other cold, a constant water stream enters the enclosure and gets in contact with the hot wall producing vapor, and then this water vapor moves to the cold wall due the temperature gradient and gets condensed. For humidifiers that depend on the contact of air and water vapor molecules on a channel, the humidifier efficiency has been proved to be dependent on channel height, inlet velocity, and heat flux. It achieved the higher evaporation rate with the narrowest channel and the lowest flow rate tested (Al-Abbasi et al., 2019).

1.5 HDH Desalination Research Proposal

This study focuses on the humidification cycle of a fully nature-powered, ocean-based HDH desalination system. Efficient humidification is an important indicator of improved freshwater production. The ocean-based concept allows the elimination of the intake and pretreatment phases, which in well-established technologies, consume as much energy as the desalination process itself (Zarzo & Prats, 2018). The proposed humidifier design makes the system discharge zero brine, which is an environmental and economic benefit. It is well known that proper brine discharge process is a high-cost operation that increases the cost of sweater desalination technologies (Morillo et al., 2014). Figure 2 shows the diagram of the humidifier unit as part of an ocean based HDH desalination concept. A heat generator will provide the hot air to the system, and the sun provides an additional heat source to raise the temperature of the air that enters the humidifier. The humidifier contains heated water that mixes with the incoming hot air yielding hot humid air at the outlet. The humidification mechanism functions by an array of wet cloth sheets placed along the air flow direction inside the humidifier unit. Wetting of those fabrics happens by means of wave overtopping, hence the water circulates through the system balancing the salt content with the surrounding water. The water content of the hot humid air is later condensed in the dehumidifier stage to collect the freshwater.

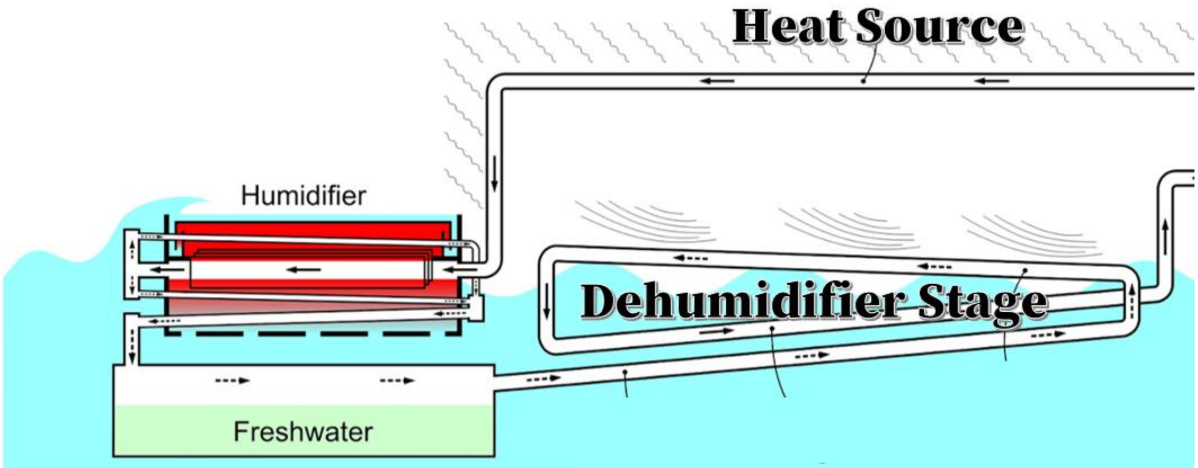

Figure 2: Proposed Ocean-Based HDH Desalination system.

The heat exchange surfaces of the system are expected to present calcium scale formations due to the saltwater running through the system (M., 2011). Different substances can rid of this fouling, however, as the system is ocean-based, it is important to consider the environmental impact on the surrounding water, apparently the Arabic gum being a biodegradable substance can solve this issue (Kazi et al., 2015). Conductive polypropylene has been studied as a feasible option as a heat transfer surface (Patti & Acierno, 2020), however, the fabrication methods of this composite material will increment the cost of the system (Chen et al., 2016).

The HDH system utilizes air as the carrier for moisture, there is no gas emission to the environment as compared to other gas carriers (Abu Arabi & Reddy, 2003). With the system being ocean-based and fully driven by renewal energies, it contributes to keep the design simple and environmentally friendly. It has been analyzed that making the air to circulate the system near the ambient pressure will provide practical and economic benefits (Yang, 2019).

1.6 Humidifier Fabrics

Fabrics can be classified into two categories based on the weaving pattern: woven fabrics, and knitted fabrics. They differentiate in how the threads form the fabric. Woven fabrics have multiple threads crossing each other, while knitted fabrics have a single or few threads that loops itself back and forth (Poincloux et al., 2018). Most of the literature investigates the fabrics for its strength or drying capability to increase user comfort. This study will be the first one to investigate the varying textile characteristics and how these attributes affect water carrying capabilities for humidification applications.

Two main characteristics of the fabrics are of importance: Water retention capacity, and water capillary wicking capability. Water retention capacity refers to the mass of water that a fabric can hold when fully saturated. Water capillary wicking refers to the ability of fabrics to absorb water through capillary affect through their porous structures.

(Lei et al., 2020) performed investigation on the wicking behavior of woven cotton fabrics. They tested several fabric specimens in a setup where a portion of the fabric area is submerged in water as seen in Figure 3. Moisture is absorbed by that area enabling the wicking to occur, but at the same time, as the water climbs up due to the capillary force, the moisture on the surface is exposed to the ambient air causing evaporation of water molecules on the sorrowing air.

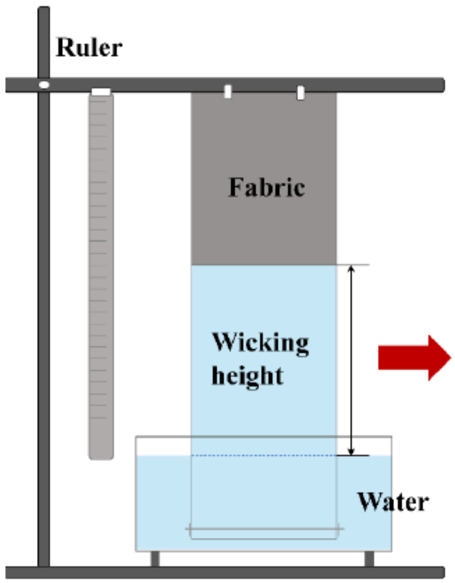

Figure 3: Concept diagram of a capillary wicking behavior.

Based on the weight loss on the water container, because of the of the moisture absorption over time, they defined those two phases of wicking exist at least on fabrics of that characteristics. At the beginning of the capillary wicking phenomenon, Phase I happens with an unsteady wicking-evaporating ratio, but later this ratio gets a dynamic balance on a plateau weight loss value, this is Phase II which happens after certain wicking height due to an equilibrium between the capillary and gravity forces. The space in between the yarns is caused by the weaving floats and it defines the pore size distribution. They divided their fabrics into two groups, one with evenly distributed floats and the other group has vertical yarns over the surface and different float size making a nonuniform structure and introducing different sizes of macropores. it has been discovered that when the degree of the pore size distribution increases, a relatively higher capillary force occurs. Therefore, fabrics with vertical capillary tubes provide connectivity points with higher water transfer speed. High porosity on a fabric is believed to enhance the speed of moisture transfer on Phase I, however findings show that floats influence more this transfer than the interlacing points. When the balance happens in Phase II, not very significant differences in water transfer speed were observed among the eight samples. Another wicking study (Parada et al.) tested custom made small scale fabrics of cotton, polyethylene terephthalate, polyamide, and polypropylene in woven and knitted patterns. They analyzed the water wicking front and the moisture content with neutron radiography and concluded that the cotton made fabrics can be classified to have quick wicking, while the other materials showed slow wicking.

For this research several commercially available fabrics with different materials and weaving patterns are tested to better understand the wicking phenomenon in fabrics at a larger scale than the presented in previous literature. Understanding the wicking behavior of fabrics and the characteristics that affect it can provide the foundation to optimize humidifiers using fabric materials.

1.7 Summary

This study will focus on the experimental testing of commercially available fabrics to characterize their water retention and wicking behavior. The characterization of the fabrics will allow us to determine the attributes that make these fabric cloths ideal for humidification processes. Additionally, this study will provide a wide range of information about the most typically used cloth materials and their behavior in contact with water that can be beneficial for other applications. Certain fabrics with contrasting wicking and water retention behavior will be selected to test their ability to humidify the air in the proposed humidifier design. The knowledge gained from the experimental data will provide a better understanding of the cloth-water interaction and set the foundation to optimize the proposed humidifier design using low-cost fabric materials.

CHAPTER II

CHARACTERIZATION OF FABRICS

2.1 Fabric classification

Our interest is to study fabrics of various materials and their ability to absorb water and retain it. 100% cotton, 100% polyester and mixtures fabrics are considered for this study. A wide diversity of weaving patterns exists, but there are two principal groups, the woven and the knitted patterns. Many of those are studied here, but we limited our scope to the most commercial and representative weaving patterns. In total, 38 fabrics with different characteristics are the subject of study. To show each of the weaving patterns, photos were taken under a microscope and a scale was added to compare their structures.

The classification proposed consist of six groups. Fabrics are first divided into Woven or Knit, then each big group subdivides into three subgroups based on the material composition: 100% Cotton, 100% Polyester, and mixtures. And then, based on their gsm value fabrics are order from highest to lowest value, Table 1 shows this classification along with the specific weaving pattern, material composition, grams per square meter (gsm), and dry mass values.

Table 1: Classification of Fabrics used with its density and mass values.

No.	Weaving Pattern	Material	gsm	mass (g)
1	Canvas Woven	100% Cotton	307.91	36.85
2	Twill Woven	100% Cotton	198.48	24.65
3	Twill Woven	100% Cotton	189.85	23.15
4	Flannel Woven	100% Cotton	179.17	22.45
5	Woven	100% Cotton	161.97	19.75
6	Crinkle Woven	100% Cotton	149.29	16.75
7	Woven	100% Cotton	144.72	18.30
8	Woven	100% Cotton	139.33	17.30
9	Woven	100% Cotton	133.69	16.00
10	Woven	100% Cotton	116.65	14.75
11	Gauze Woven	100% Cotton	105.88	13.15
12	Basketweave	100% Polyester	305.26	38.60
13	Woven	100% Polyester	150.65	19.05
14	Chiffon Fabric	100% Polyester	68.80	8.70
15	Seersucker Woven	65% Polyester 35% Cotton	112.30	14.20
16	Woven	80% Polyester 20% Cotton	104.39	13.20
17	Woven	65% Polyester 35% Cotton	103.99	13.15
18	Woven	65% Polyester 35% Cotton	99.64	12.60
19	Waffle Terry Knit	100% Cotton	208.38	26.35
20	Pique Knit	100% Cotton	205.75	25.20
21	Fleece Knit	100% Cotton	205.29	24.80
22	Interlock Knit	100% Cotton	203.48	25.50
23	Rib knit and Warp Knit	100% Cotton	191.77	22.95
24	Rib knit and Warp Knit	100% Cotton	166.86	21.10
25	Jersey Knit	100% Cotton	139.53	15.95
26	Jersey Knit	100% Cotton	131.13	16.10
27	Double Plain Knit	100% Cotton	112.91	14.15
28	Scuba Knit	100% Polyester	199.88	25.05
29	Pique Knit	100% Polyester	198.10	25.05
30	Travel Knit	100% Polyester	111.90	14.15
31	Interlock Knit	100% Polyester	100.65	12.50
32	Rib Knit (1x1)	95% Cotton 5%Elastane	327.79	43.70
33	Rib Knit (1x1)	96% Cotton 4% Elastane	241.90	28.95

Table 1, cont.

No.	Weaving Pattern	Material	gsm	mass (g)
34	Rib Dryline Knit	92% Polyester 8% Elastane	202.45	25.60
35	Liverpool Knit	96.5% Polyester 3.5% Elastane	197.70	25.00
36	Rib Knit (2x2)	96% Polyester 4% Elastane	194.15	24.55
37	French Terry	80% Polyester 16% Rayon 4% Elastane	193.07	24.85
38	Purl Knit	89% Polyester 11% Elastane	162.91	20.60

Density classifications consist in lightweight fabrics (0-139 gsm), mediumweight fabrics (140-179 gsm), and heavyweight fabrics (180+ gsm). Due to the large number of fabrics used and the many variables of each fabric, data analysis can become overwhelming, and it is better to reduce the variables to identify the main contributor to a pattern in performance. Hence, testing results are compared by first classifying it by woven or knit, then by the material composition, and later by their mass per area. In the case of mixture material fabrics, these are compared with similar material percentage composition and then by a gradual changing composition to observe the effect of material composition on the results. By using this approach, general characteristics are investigated to find what makes a fabric to have a good performance in water retention and water capillary wicking. and then be able to tell which characteristics are preferable to select from the most commercial fabrics.

2.2 Weaving Patterns

The weaving pattern name usually does not provide enough detailed information on the geometry and characteristics of the fabric. In this section, we discuss the most important attributes that distinguish each fabric shown in Table 1. The three most common woven patterns are the simple weave, twill weave, and basketweave. All types of woven fabric are made by interweaving while knitted fabrics are made by interloping (Grishanov et al., 2009). Simple weaves have the warp and weft threads interweaving over and under each other, Twill weave have diagonal ribs on its weaving, and basketweave is made by putting together several yarns in the weaving at the time. These patterns can be appreciated in the Figure 4. Chiffon fabrics have a plain weave pattern, but it is thin with big spaces between the yarns. Crepe or Crinkle fabrics have a plain weave as well, but its surface can be felt rough because the yarns are twisted in the weave. Flannel fabrics have a simple weave, but with a little more slack as compared to other fabrics, also, one of its sides is brushed, creating the pilling effect on the surface of the fabric ("Plain Weave - Structure, Properties, Uses & Types," 2021).

Single Jersey fabric is one of the more widely used for clothing applications. (Fouda et al., 2015). A diagram of the typical Single Jersey interloping structure can be observed in Figure 5a. Purl knit distinguishes in structure by having the stich loop wrapping the upper row in a back-to-front manner as opposed to front-to-back as the knit stiches of the Single Jersey. When observed in pictures or diagrams these purl stiches are seen as small curves on the knitting structure. Utilizing knit stiches and purl stiches in alternating rows is how Rib knit is made (Wadekar et al., 2020). Figure 5 shows diagrams of the most common types of knit structures. Rib knit stiches alternation leads to the creation of a wide variety of patterns, the nomenclature used indicates how the alternation is, for example, Rib knit "1x1" indicates a one-by-one alternation, while “2x2” indicates two knit stiches after two purl stiches, and so on. In the fabric, this alternation looks like having some “ribs” of fabric divided by some space (Bosforus Textile | Rib Knit Fabric, n.d.). Interlock knit resembles a doble layer Rib knit but both layers are interknitted. Generally, this make the fabric to be more stable than regular rib knit, both sides look identical, the ends do not curl like the Single Jersey, but its thickness is the double (Das et al., 2017). In warp knitting the loops are formed vertically creating more interloping, this makes the fabric more stable dimensionally. Tricot knit pattern is one of the patterns that can be created this way (Gupta & Edwards, 2019).

Pique knit is a two-layer fabric, that usually have a porous side and a smooth side, this is due to its application in sport clothes. Several types of pique knits exist, it has been found in literature that one having a hive structure helps to break the surface tension of water allowing water penetration and capillary wicking (Fern et al., 2018). French Terry is a fabric with two different sides as well, one side displays loops, while the other have a smooth surface. This is a characteristic knitting pattern used for winter clothes, and it has good stretchability. Fleece fabric is also utilized for the same type of applications, but this one usually have a larger amount of pilling on its surface (“What Is French Terry?,” 2021). Scuba knit is a double layer fabric, typical structure consists of a layer of neoprene between layers of polyester and elastane (What Is Scuba Fabric?, 2021). Liverpool fabrics feature a jacquard knitting pattern and a texturized side, so it is usually used for ornamental purposes (What Is Jacquard Fabric, n.d.). Waffle terry knit features a honeycomb structure with threads combined in warp and weft floats around a weave center forming rectangles (“Waffle Fabric,” 2022).

In Figure 6 microscope photos of the 18 woven fabrics used in this research are presented, and in Figure 7 microscope photos of the knitted fabrics are shown.

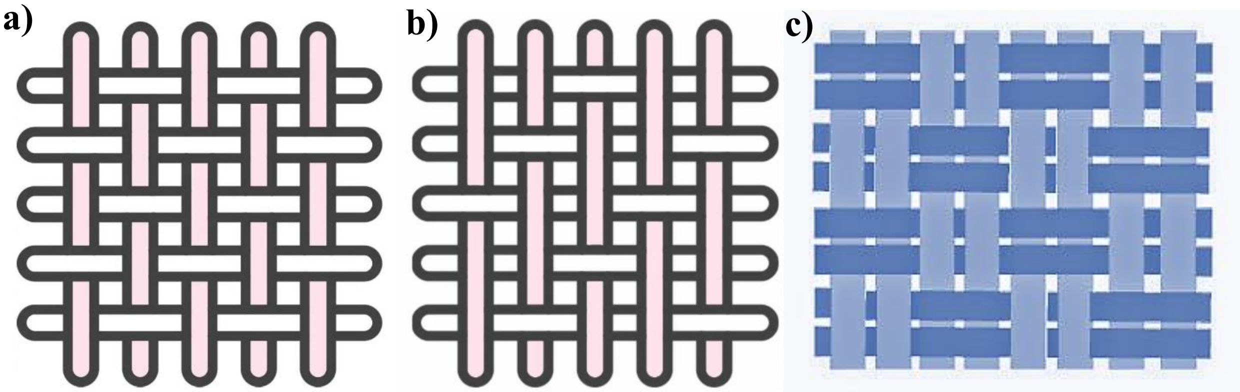

Figure 4: Three common woven patterns and the ones utilized for testing. a) Plain Weave, b) Twill Weave, c) Basket Weave.

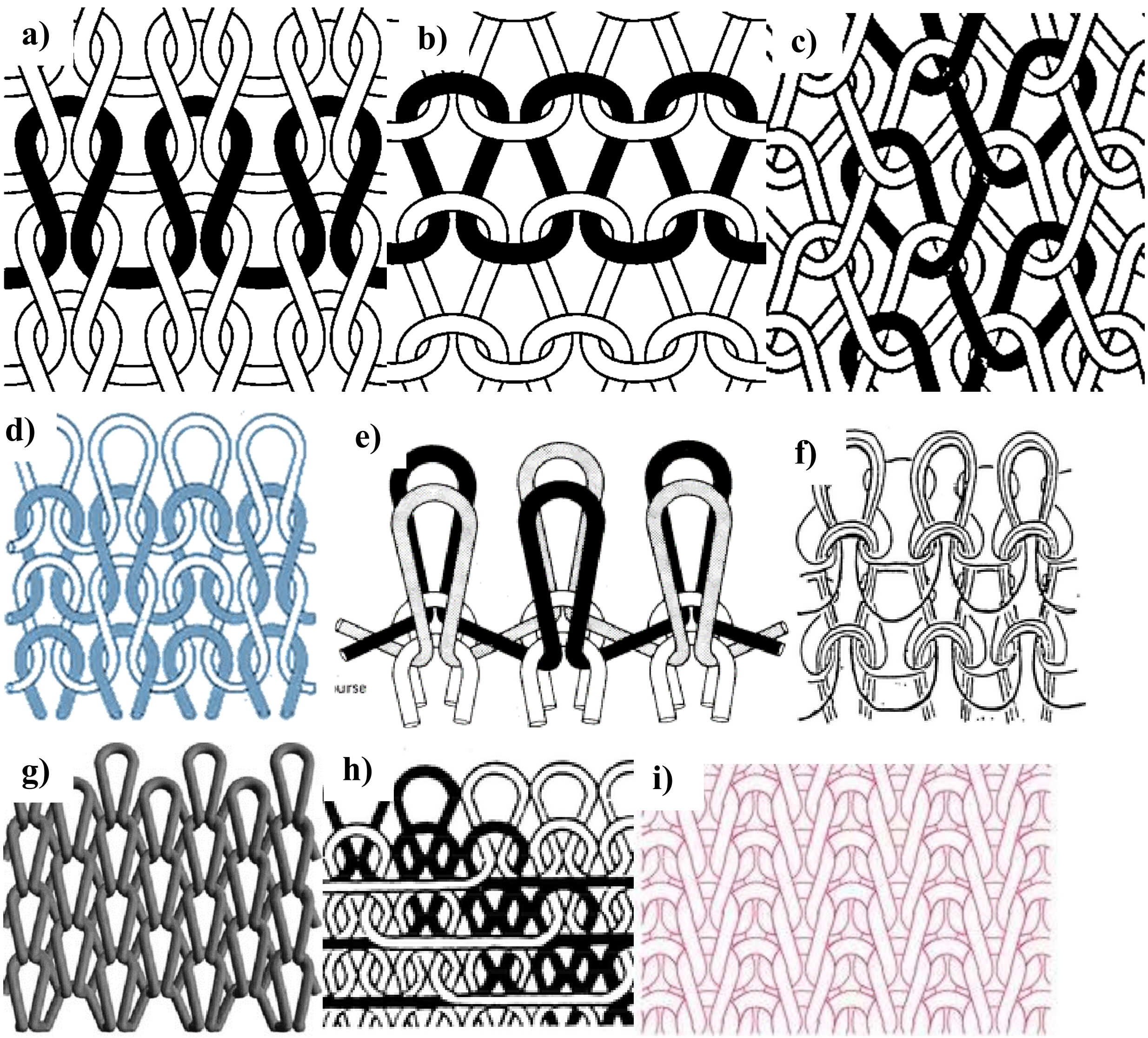

Figure 5: Common knit patterns utilized. a) Simple knit, b) Purl knit, c) Warp knit, d) Rib knit, e) Interlock knit, f) Double face French terry knit, g) Pique knit, h) Jacquard knit, i) Scuba knit (ISO 8388:1998(En), Knitted Fabrics — Types — Vocabulary, n.d.).

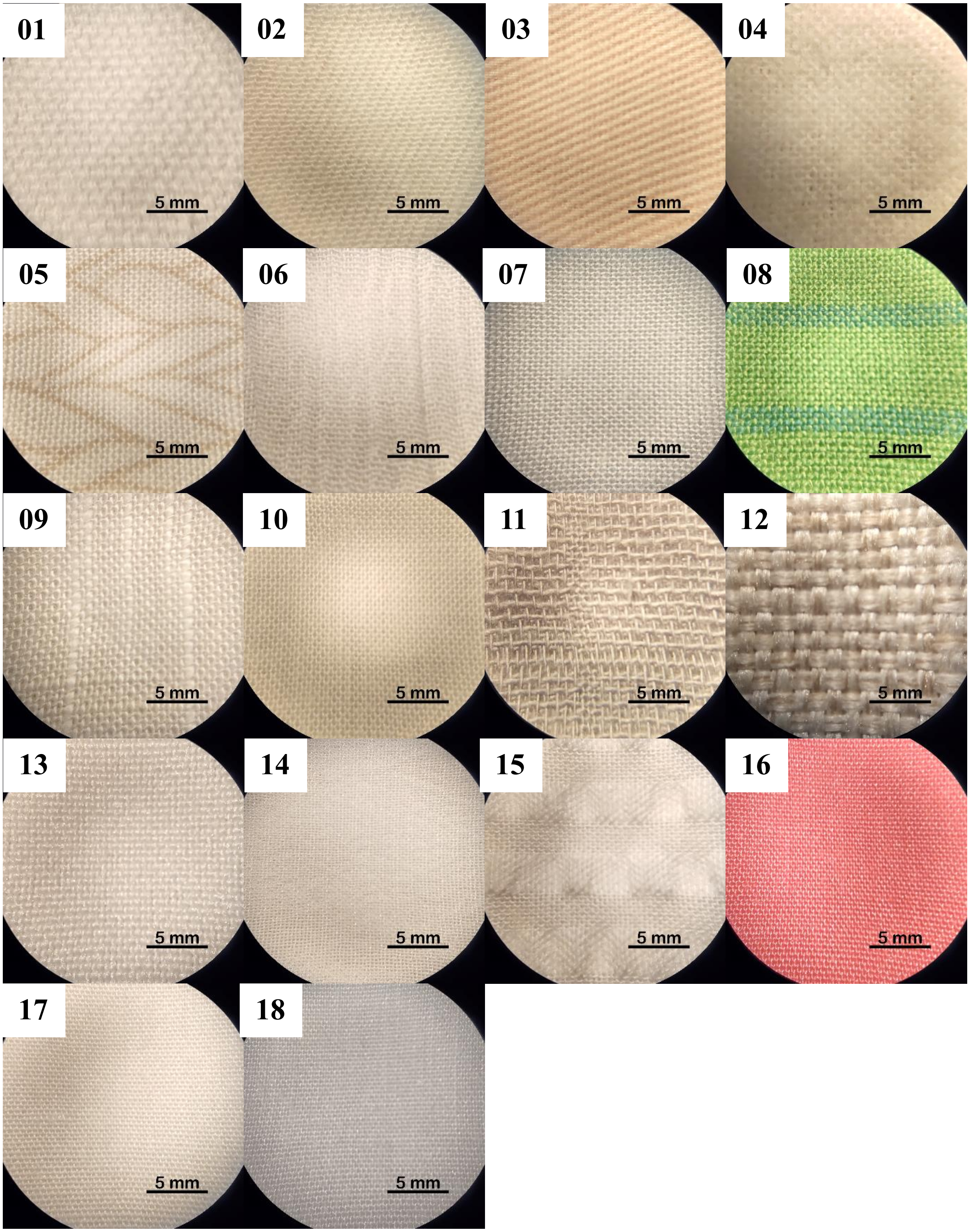

Figure 6: Pictures of the Woven Fabrics.

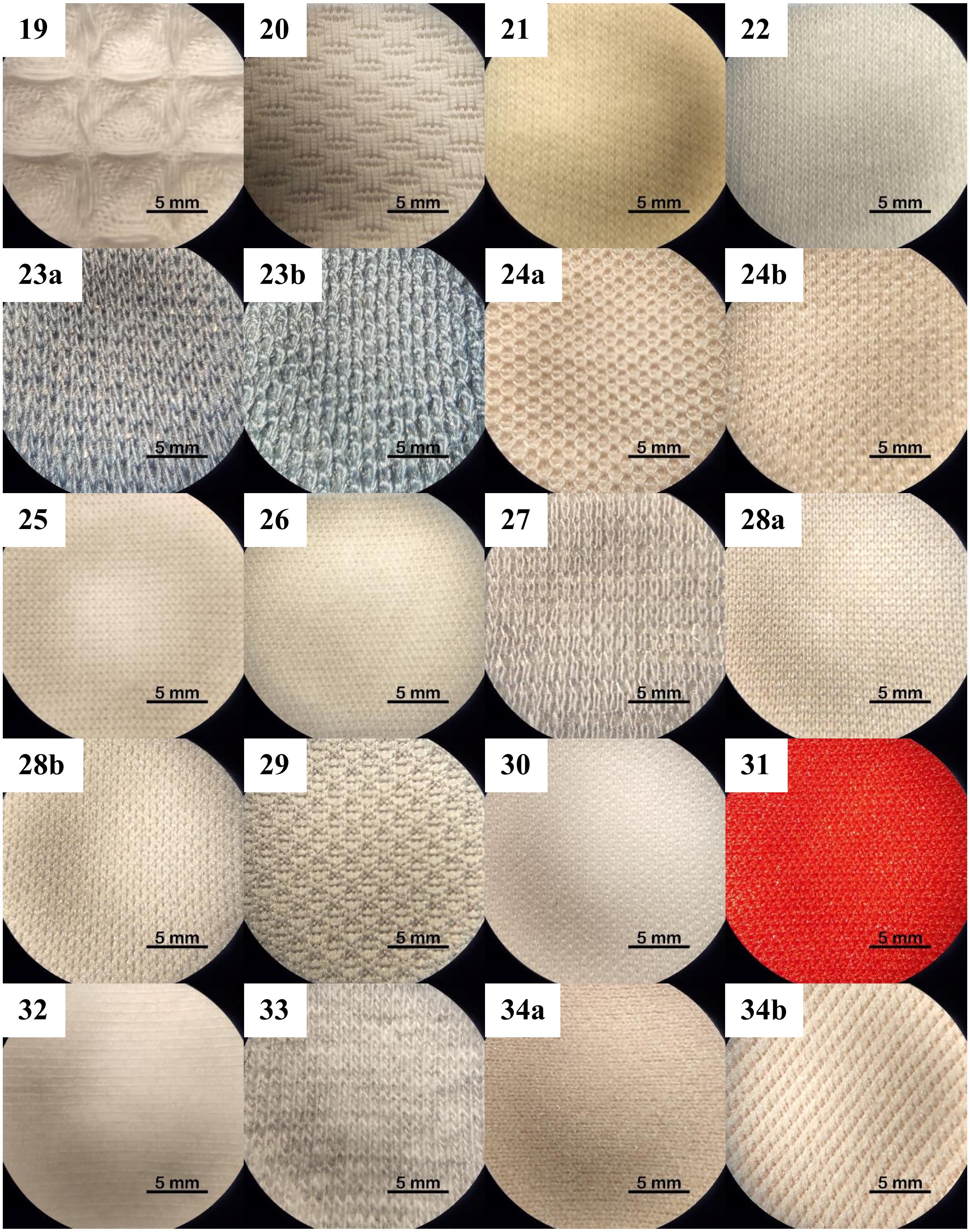

Figure 7: Pictures of the Knitted Fabrics, showing their sides if they have.

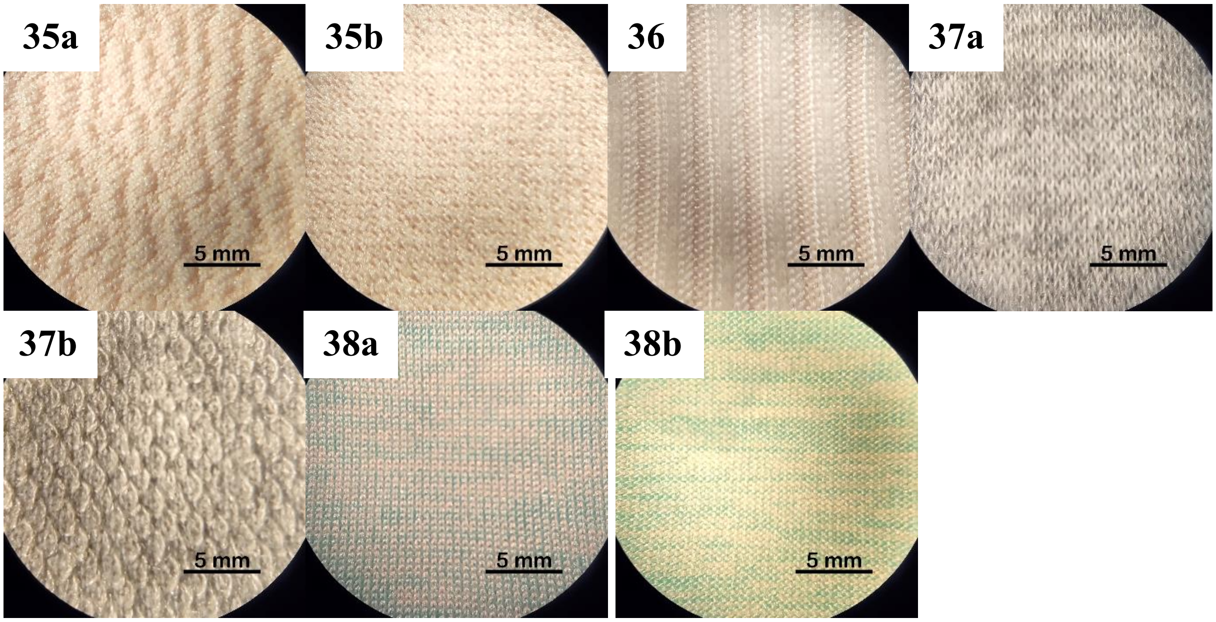

Figure 7, cont.

2.2.1 Weaving Pattern Structure Variation Degree

From the literature review it has been found that an irregular weaving structure of the fabric introduces a changing pore size distribution that creates stronger capillary forces than fabrics with a regular weaving pattern. Therefore, fabrics are classified by a structure variation degree that will allow to better characterize the wicking performance of each of the fabrics for this study. Degree A is assigned to fabrics with a geometrically constant weaving structure, while degree B is given to fabrics with a constant non-geometrical structure. From these definitions, three sub-categories are assigned; using numbers from 1 to 3 which define the level of variation on the structure. Level 1 is given to fabrics with a simple repeating pattern, level 2 is given to fabrics with a structure having constant minor variations, while level 3 is for fabrics with variations that introduce big modifications on a constant structure. Table 2 shows the degree of variation given to every fabric.

Table 2: Structure Variation Degree given to each fabric.

No.	Weaving Pattern	Structure Variation Degree
1	Canvas Woven	A2
2	Twill Woven	A2
3	Twill Woven	A2
4	Flannel Woven	A3 (Pilling)
5	Woven	A1
6	Crinkle Woven	A2
7	Woven	A1
8	Woven	A1
9	Woven	A1
10	Woven	A1
11	Solid Woven	A2 (Pilling)
12	Basketweave	A2
13	Woven	A1
14	Chiffon Fabric	A1
15	Seersucker Woven	A3
16	Woven	A1
17	Woven	A1
18	Woven	A1
19	Waffle Terry Knit	B3
20	Pique Knit	B3
21	Fleece Knit	B2 (Pilling)
22	Interlock Knit	B1
23	Rib knit and Warp Knit	B3
24	Rib knit and Warp Knit	B3
25	Jersey Knit	B1
26	Jersey Knit	B1
27	Double Plain Knit	B1
28	Scuba Knit	B2
29	Pique Knit	B3
30	Travel Knit	B1
31	Interlock Knit	B1
32	Rib Knit	B2 (Pilling)
33	Rib Knit	B1
34	Rib Dryline Knit	B3
35	Liverpool Knit	B2
36	Rib Knit	B2
37	French Terry	B2
38	Purl Knit	B1

2.2.2 Woven Threads per Inch (TPI)

In the woven group, some fabrics feel softer than others, this is due the looseness or tightness of the woven pattern. As the fabric is more closely weaved, less space exists in between yarns. For those reasons, a parameter defined as thread per inch (TPI) has been determined for the woven fabrics only. This parameter can give an idea of how densely the woven structure is conformed. Table 3 shows the TPI for each woven fabric. Denser fabrics can have less air space in between the yarns, and lower density fabrics have more space in between the yarns due to a looser weaving,

Table 3: Woven Fabrics TPI Definitions.

No.	Weaving Pattern	Threads per Inch
1	Canvas Woven	77
2	Twill Woven	53
3	Twill Woven	136
4	Flannel Woven	51
5	Woven	75
6	Crinkle Woven	85
7	Woven	69
8	Woven	53
9	Woven	53
10	Woven	80
11	Solid Woven	69
12	Basketweave	21
13	Woven	45
14	Chiffon Fabric	85
15	Seersucker Woven	83
16	Woven	112
17	Woven	115
18	Woven	112

2.2.3 Pilling Level

Pilling is defined as the loose strands or fibers that form on a piece of fabric. Defining the pilling level on the fabric surface will help to characterize the performance on water retention and capillary wicking. Three levels have been defined: 0 for having no pills (Figure 8a), 1 for having occasional and not evenly distributed pills (Figure 8b), 2 for a small number of pills all over the surface (Figure 8c), and 3 for having pills covering the entire surface (Figure 8d). It is important to mention that the wearing of the fabric surface could yield the yarns to be brushed, creating pilling. For this research, all fabrics were handwashed to introduce weariness at an even degree before starting formal testing. Table 4 summarizes the pilling level for all fabrics used in this study.

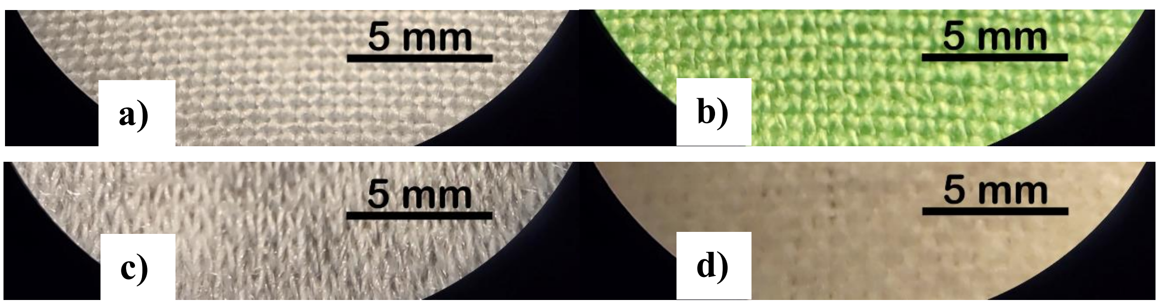

Figure 8: Picture Comparison of the pilling level among some fabrics. a) Level 0. b) Level 1. c) Level 2. d) Level 3.

Table 4: Pilling level for each fabric.

No.	Weaving Pattern	Pilling Level	No.	Weaving Pattern	Pilling Level
1	Canvas Woven	1	20	Pique Knit	1
2	Twill Woven	1	21	Fleece Knit	3
3	Twill Woven	1	22	Interlock Knit	2
4	Flannel Woven	3	23	Rib knit and Warp Knit	2
5	Woven	1	24	Rib knit and Warp Knit	2
6	Crinkle Woven	1	25	Jersey Knit	2
7	Woven	0	26	Jersey Knit	2

Table 4, cont.

No.	Weaving Pattern	Pilling Level	No.	Weaving Pattern	Pilling Level
8	Woven	1	27	Double Plain Knit	2
9	Woven	1	28	Scuba Knit	0
10	Woven	1	29	Pique Knit	0
11	Solid Woven	2	30	Travel Knit	0
12	Basketweave	1	31	Interlock Knit	0
13	Woven	0	32	Rib Knit	3
14	Chiffon Fabric	0	33	Rib Knit	1
15	Seersucker Woven	1	34	Rib Dryline Knit	1
16	Woven	1	35	Liverpool Knit	0
17	Woven	1	36	Rib Knit	1
18	Woven	1	37	French Terry	2
19	Waffle Terry Knit	2	38	Purl Knit	0

2.3 Fabric Testing Parameters

For all the testing, a square fabric specimen of 14 by 14 inches was cut and each one was handwashed thoroughly two times with fabric soap to remove any influencing substance before testing. Because the specimens were slightly deformed at washing, the area and dry mass weights measurements were taken after this process. Before each test, all fabrics were completely dry to start from the same constant condition.

2.4 Water Retention Testing

This section contains the results of water retention capability of all the fabrics. The purpose of investigating the water retention capacity of each of the fabrics is to characterize the factors that affect their capacity to hold water. The amount of water that a fabric can hold is critical to improve the air humidification since it provides a higher number of water molecules available for the air to carry away as moisture.

2.4.1 Setup

The setup consists of a custom-made acrylic structure frame where the cloth is hanged by binder clips without touching a measuring scale, therefore as water is injected on both sides of the fabric, the scale will display the increment in mass. When the injection process is happening, the fabric reaches a saturation point where the dripping balances the water injection, the dripping water falls in a tray placed under the fabric and is supported on an external base. Diagrams of the setup are presented in Figure 9. A photograph of the actual setup is displayed in Figure 10.

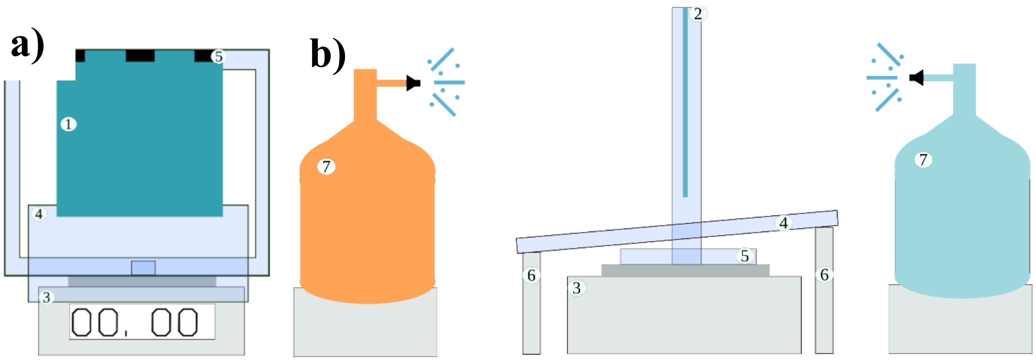

Figure 9: Schematic of the Water Retention Setup. a) Front view, b) Side view. 1. Fabric, 2. Frame, 3. Scale, 4. Tray, 5. Binder clips, 6. Tray Supports, 7. Water Sprayers.

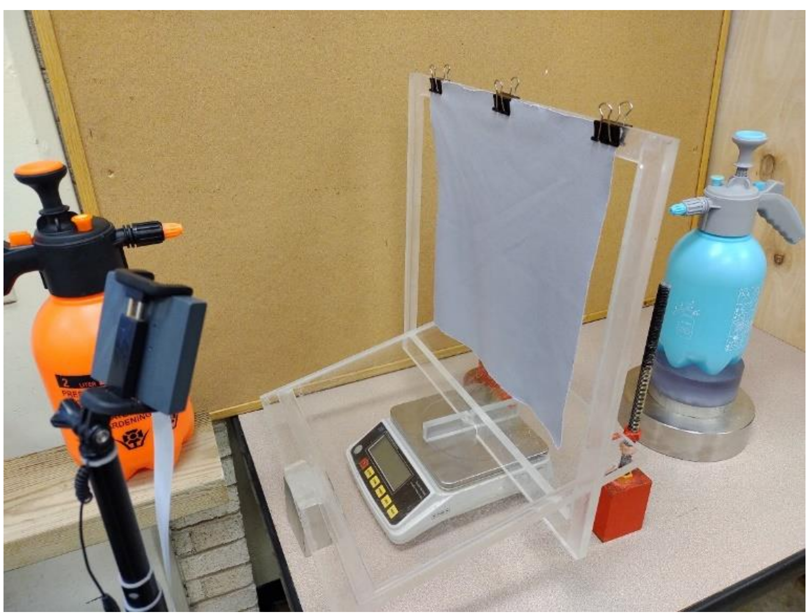

Figure 10: Photo of the Water Retention setup.

2.4.2 Testing Parameters

Constant parameters were defined to run all the testing under the same conditions. The scale measures only the fabric mass with the water mass being hold by the fabric. To measure the point of full saturation of each fabric, the two sprayers are placed on each side to completely wet the fabric. Ambient temperature tap water is sprayed for 100 seconds at a constant injection rate of 10.6 g/s for the back sprayer, and 10.8 g/s for the front sprayer. When the water saturation period finalizes, the water injection is stopped, so the dripping phase begins followed by the drying phase. The total testing time is 20 minutes. Data recollection was done by video recording the scale display during all the testing time and collect the weight reading every 20 seconds. All the testing was done in similar ambient conditions inside an air-conditioned laboratory. Ambient temperature was maintained around 20 °C ±5°C, and the Relative Humidity at 58% RH ±10%.

2.4.3 Results

Results show that when the water injection occurs, the mass weight of the fabric reaches a steady saturation point due to a balance between the dripping and the injection rate. This balance is maintained for 100 seconds. A sudden drop of the mass weight is observed when the injection is removed. This drop is approximated with a slope coefficient k0 for this study, and it was observed to be different for each fabric. a relatively big coefficient represents the fabric releasing water content rapidly and a small number represents a slower dripping. Later, when the dripping slows down enough, the water release continues at a slower rate, this is because evaporation is now dominating. A new slope k1 was determined for the weight mass values at the end of the testing time, here a small coefficient represents the fabric having a good retention of the water content. Since the injection procedure is the same for all fabrics, is of our interest to know the behavior of the fabric to hold water right after the injection ends. For that reason, injection phase is not being showed in the data. Figure 11 shows the water retention of a fabric without the injection phase. Figure 12 shows the slope k1 of fabric No.20. In Figure 13 the water retention data is normalized by dividing the water content in each moment by the mass of the dry fabric. This nondimensional value represents how many times the fabric can hold their dry mass value as water content. As the values get closer to one, it means that the fabric it is drying.

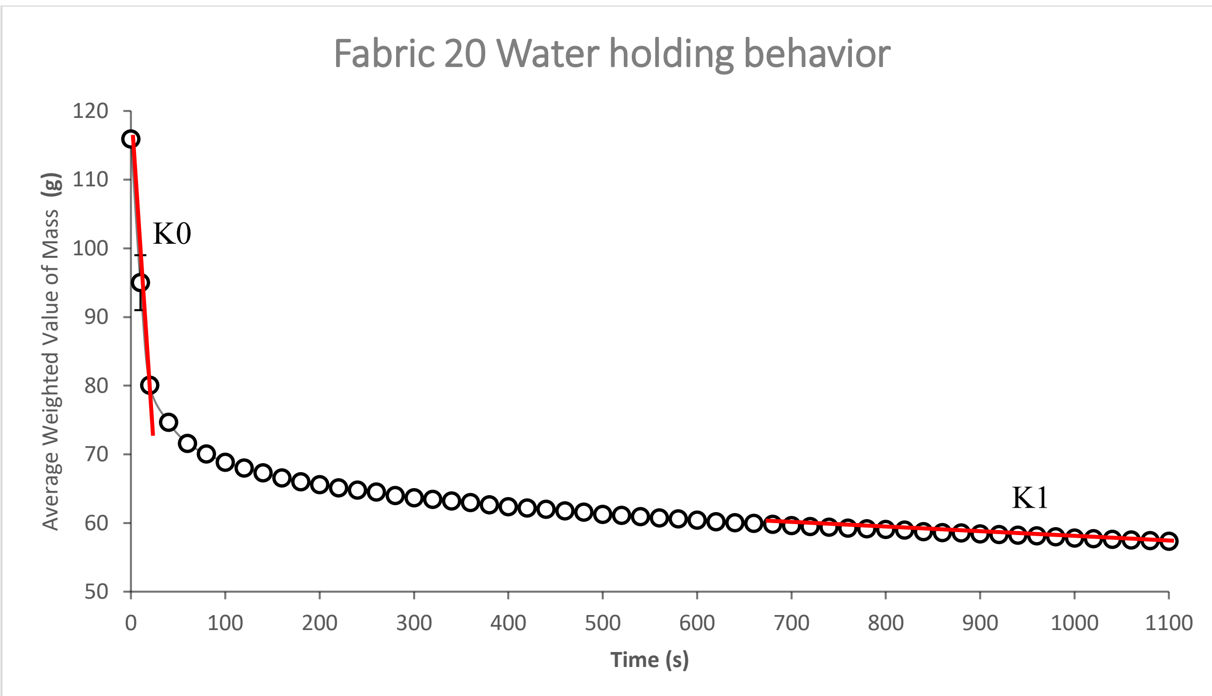

Figure 11: Plot showing the typical form of the water retention behavior.

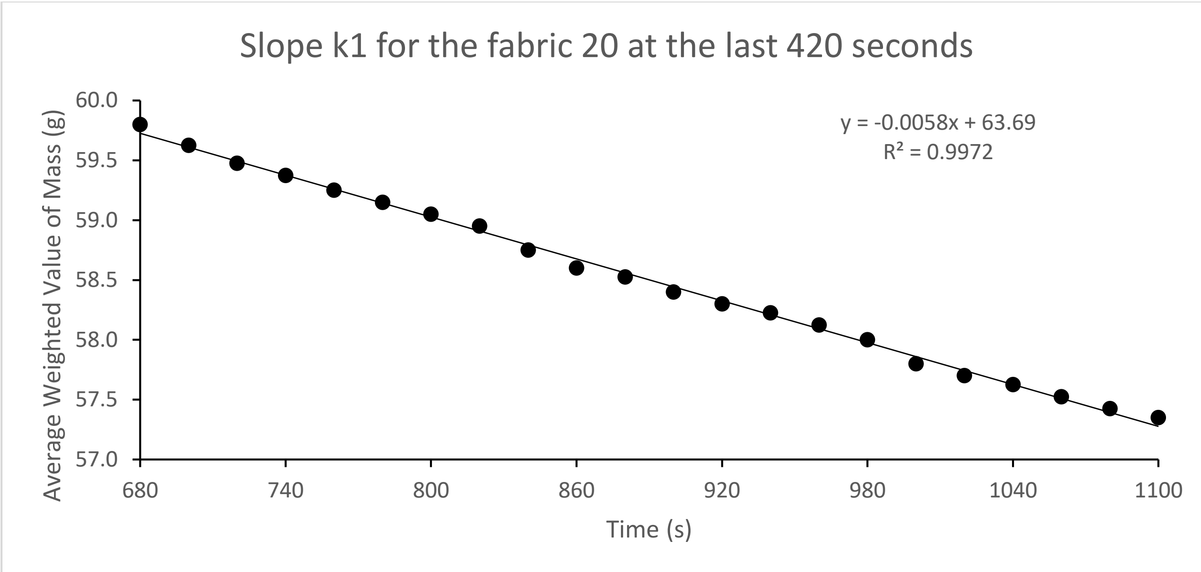

Figure 12: Plot showing the slope of the line that fits the data on last 420 seconds.

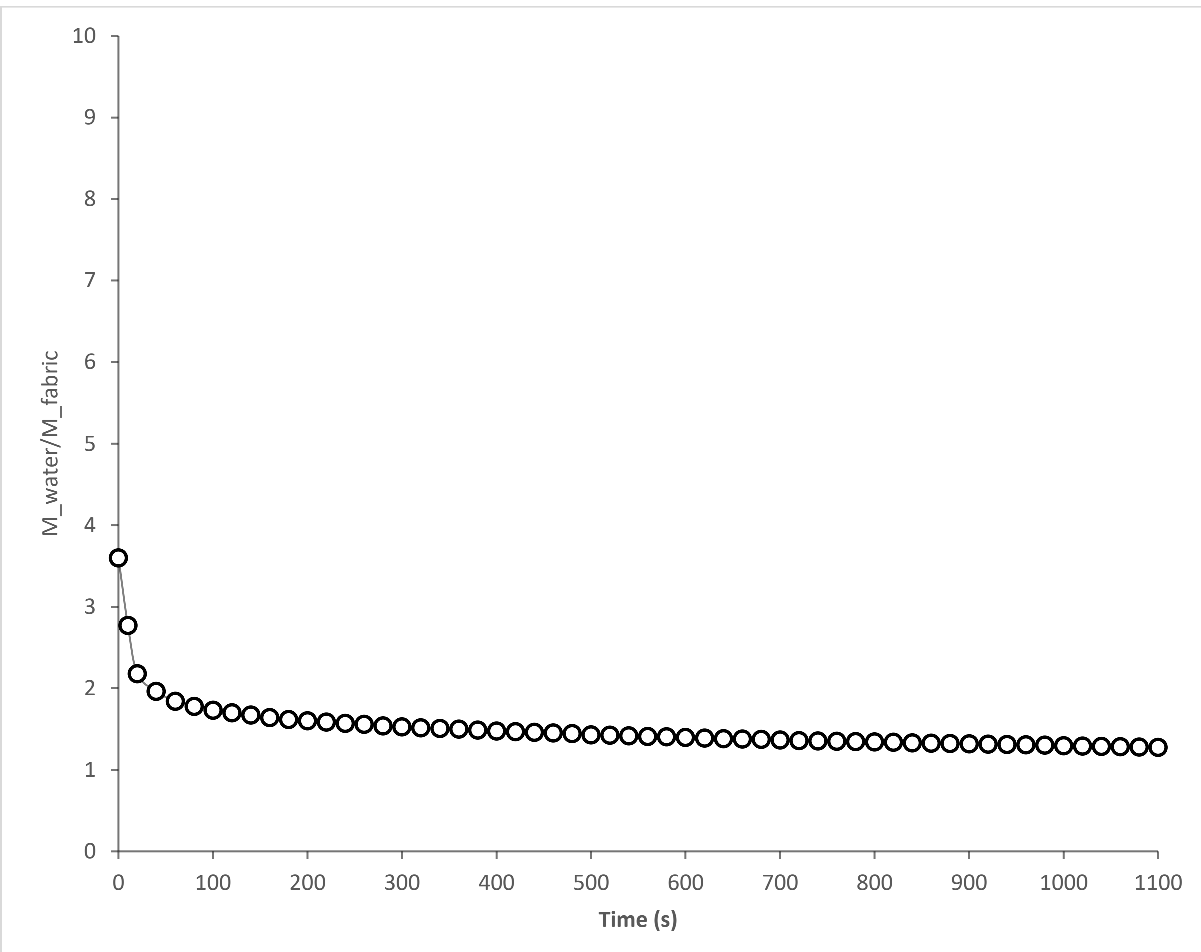

Figure 13: Water Content Normalized by the dry mass of the water retention data.

The Water Retention Measure (WRM) is defined by the product of the Normalized Water Content at the end (1100 seconds) and the ratio k1/k0. This Ratio describes how the water retention changed from the beginning to the end, the more abrupt the slope change from k0 to k1, the smaller the ratio value would be, and if the transition is smother, this ratio value would be less small. Therefore, the WRM describes how a fabric hold the water content having in consideration its retention behavior over time. Hence, WRM is higher for fabrics behaving by retaining the water in a steady way with less steep drop from the saturation point. Those results can be seen in Table 5.

Table 5: Water Retention Results ordered by the fabrics classification.

No.	Weaving Pattern	Material	g/m^2	SVD	Dry mass (g)	K0 (g/s)	K1 (g/s)	Wet mass (g)	NWC	WRM
1	Canvas Woven	100% Cotton	307.91	**A2**	36.9	**2.592**	**0.0067**	85.2	**1.31**	**0.0034**
2	Twill Woven	100% Cotton	198.48	**A2**	24.7	**2.690**	**0.0056**	58.9	**1.39**	**0.0029**
3	Twill Woven	100% Cotton	189.85	**A2**	23.2	**2.255**	**0.0062**	52.4	**1.26**	**0.0035**
4	Flannel Woven	100% Cotton	179.17	**A3 (P)**	22.5	**3.547**	**0.0077**	79.1	**2.52**	**0.0055**
5	Woven	100% Cotton	161.97	**A1**	19.8	**1.448**	**0.0062**	39.3	**0.99**	**0.0042**
6	Crinkle Woven	100% Cotton	149.29	**A2**	16.8	**3.498**	**0.0059**	41.1	**1.45**	**0.0024**
7	Woven	100% Cotton	144.72	**A1**	18.3	**1.492**	**0.0056**	37.9	**1.07**	**0.0040**
8	Woven	100% Cotton	139.33	**A1**	17.3	**1.573**	**0.0072**	44.3	**1.56**	**0.0072**
9	Woven	100% Cotton	133.69	**A1**	16.0	**2.520**	**0.0062**	40.6	**1.54**	**0.0038**
10	Woven	100% Cotton	116.65	**A1**	14.8	**2.432**	**0.0061**	32.2	**1.18**	**0.0030**
11	Gauze Woven	100% Cotton	105.88	**A2 (P)**	13.2	**3.550**	**0.0072**	49.3	**2.75**	**0.0056**
12	Basketweave	100% Polyester	305.26	**A2**	38.6	**2.410**	**0.0053**	93.5	**1.42**	**0.0031**

Table 5, cont.

No.	Weaving Pattern	Material	g/m^2	SVD	Dry mass (g)	K0 (g/s)	K1 (g/s)	Wet mass (g)	NWC	WRM
13	Woven	100% Polyester	150.65	**A1**	19.1	**1.980**	**0.0054**	43.4	**1.28**	**0.0035**
14	Chiffon Fabric	100% Polyester	68.80	**A1**	8.7	**0.825**	**0.0051**	14.6	**0.67**	**0.0042**
15	Seersucker Woven	65% Polyester 35% Cotton	112.30	**A3**	14.2	**2.692**	**0.0066**	34.7	**1.44**	**0.0035**
16	Woven	80% Polyester 20% Cotton	104.39	**A1**	13.2	**2.818**	**0.0053**	23.6	**0.79**	**0.0015**
17	Woven	65% Polyester 35% Cotton	103.99	**A1**	13.2	**2.445**	**0.0058**	25.1	**0.91**	**0.0022**
18	Woven	65% Polyester 35% Cotton	99.64	**A1**	12.6	**2.638**	**0.0061**	22.9	**0.82**	**0.0019**
19	Waffle Terry Knit	100% Cotton	208.38	**B3**	26.4	**6.402**	**0.0080**	89.7	**2.40**	**0.0030**
20	Pique Knit	100% Cotton	205.75	**B3**	25.2	**2.093**	**0.0058**	57.3	**1.27**	**0.0035**
21	Fleece Knit	100% Cotton	205.29	**B2 (P)**	24.8	**2.873**	**0.0082**	99.8	**3.02**	**0.0086**
22	Interlock Knit	100% Cotton	203.48	**B1**	25.5	**1.451**	**0.0066**	98.3	**2.85**	**0.0130**
23	Rib knit and Warp Knit	100% Cotton	191.77	**B3**	23.0	**2.645**	**0.0072**	65.9	**1.87**	**0.0051**
24	Rib knit and Warp Knit	100% Cotton	166.86	**B3**	21.1	**2.877**	**0.0075**	59.1	**1.80**	**0.0047**
25	Jersey Knit	100% Cotton	139.53	**B1**	16.0	**2.400**	**0.0063**	46.0	**1.88**	**0.0049**

Table 5, cont.

No.	Weaving Pattern	Material	g/m^2	SVD	Dry mass (g)	K0 (g/s)	K1 (g/s)	Wet mass (g)	NWC	WRM
26	Jersey Knit	100% Cotton	131.13	**B1**	16.1	**2.433**	**0.0074**	50.0	**2.10**	**0.0064**
27	Double Plain Knit	100% Cotton	112.91	**B1**	14.2	**3.260**	**0.0086**	45.4	**2.21**	**0.0058**
28	Scuba Knit	100% Polyes-ter	199.88	**B2**	25.1	**1.407**	**0.0092**	68.5	**1.74**	**0.0114**
29	Pique Knit	100% Polyes-ter	198.10	**B3**	25.1	**2.060**	**0.0062**	65.9	**1.63**	**0.0049**
30	Travel Knit	100% Polyes-ter	111.90	**B1**	14.2	**1.232**	**0.0064**	46.0	**2.25**	**0.0117**
31	Interlock Knit	100% Polyes-ter	100.65	**B1**	12.5	**1.283**	**0.0070**	36.4	**1.91**	**0.0104**
32	Rib Knit	95% Cotton 5%Elas-tane	327.79	**B2 (P)**	43.7	**2.663**	**0.0082**	145.5	**2.33**	**0.0072**
33	Rib Knit	96% Cotton 4% Elastane	241.90	**B1**	29.0	**2.617**	**0.0071**	98.0	**2.38**	**0.0065**
34	Rib Dryline Knit	92% Polyes-ter 8% Elastane	202.45	**B3**	25.6	**1.765**	**0.0082**	85.8	**2.35**	**0.0109**
35	Liverpool Knit	96.5% Polyes-ter 3.5% Elastane	197.70	**B2**	25.0	**2.105**	**0.0114**	76.9	**2.08**	**0.0112**
36	Rib Knit	96% Polyes-ter 4% Elastane	194.15	**B2**	24.6	**2.187**	**0.0078**	67.8	**1.76**	**0.0063**

Table 5, cont.

No.	Weaving Pattern	Material	g/m^2	SVD	Dry mass (g)	K0 (g/s)	K1 (g/s)	Wet mass (g)	NWC	WRM
37	French Terry	80% Polyester 16% Rayon 4% Elastane	193.07	**B2**	24.9	**2.482**	**0.0077**	64.9	**1.61**	**0.0050**
38	Purl Knit	89% Polyester 11% Elastane	162.91	**B1**	20.6	**1.513**	**0.0055**	53.7	**1.61**	**0.0058**

2.4.4 Discussion

The analysis was separated in six groups to better describe the different effects of each factor (material, weaving pattern, density, etc) on the water retention of the fabrics. Three subgroups have been defined by their mass per area value (density). Lightweight fabrics can have from 0 to 139 gsm, mediumweight fabrics have from 140 gsm to 179 gsm, and heavyweight fabrics have more than 180 gms.

From Figure 14, Figure 16, and Figure 18 we can see that for the majority of fabrics, the normalized water content looks very similar, their values at 1100 seconds range from 1 to 1.5. It is of our interest to determine which is the dominant factor that affect the water holding capacity. In the case of the medium weight group, we can observe that fabric No. 05 have a worse performance than fabric No. 6 even that it is denser. Two cases stand out by much from the rest, Fabrics No. 11 and No. 04, exist a huge difference in their grams per square meter value, and they still match by the end water retention value (Figure 20), which is bigger than the values of the rest fabrics, their k1 and k2 slope values are also very similar (0.007, and 3.5 respectively for both). Therefore, an option to explain their very similar performance must be due some common factor in their structures. Both have a simple woven pattern, and if we investigate their Structure Variation Degree (SVG) Fabric No.4 have a A3, and Fabric No. 11 an A2. This is because both have a significant amount of pilling over their surface, so this is the identified condition which boost the Water Retention of the fabrics. And as Fabric 11 is the less dense and still stands on the top performers, it can be said that the density is not dominant on the performance at least for these groups. When analyzing the Water Retention Measure (WRM) on Figure 15 it can be noted that Fabric No. 8 performs the best by having a higher value than Fabric No. 11 even that on the NWC, this last one is better. This can be explained by remembering that WRM considers the changes in the slopes k0 and k1, so this fabrics by having a lower value means that it have to release more water content in a more sudden way (high k0 value) to actually reach a stable water releasing rate (low k1 value), but even by this, in absolute terms this fabric do still hold more times its dry mass value in water mass than Fabric No. 8. This last one will release its water content in a smoother way because initially its saturation point is not as high as the one from Fabric No. 11. Medium weight fabrics shows a very similar behavior (Figure 16) as lightweight fabrics, variation in density seems to do not dominate the performance. In terms of WRM (Figure 17) the best fabrics do agree with the NWR results. It may be important to mention the low WRM of Fabric No. 6 that has a Crinkle Woven A2 pattern, for now it cannot be identified as a good performer. The rest of the patterns apart from Flannel Woven with a lot of pilling, seem to score near the average WRM of 0.0056 with an A1 structure. Fabric No. 5 can be observed in Figure 6 and it have a printed surface, apparently that does not affect the Water Retention.

Heavyweight fabrics NWC behavior (Figure 18) and WRM values (Figure 19) are closely related even that they come from different densities and weaving patterns. Again, density it not seen as having a clear influence. Canvas Woven and Twill Woven patterns can be identified as operating on values below the average, so considering that less denser fabrics have performed better, this may suggest that having denser fabric material over the same area will not optimize the water retention process.

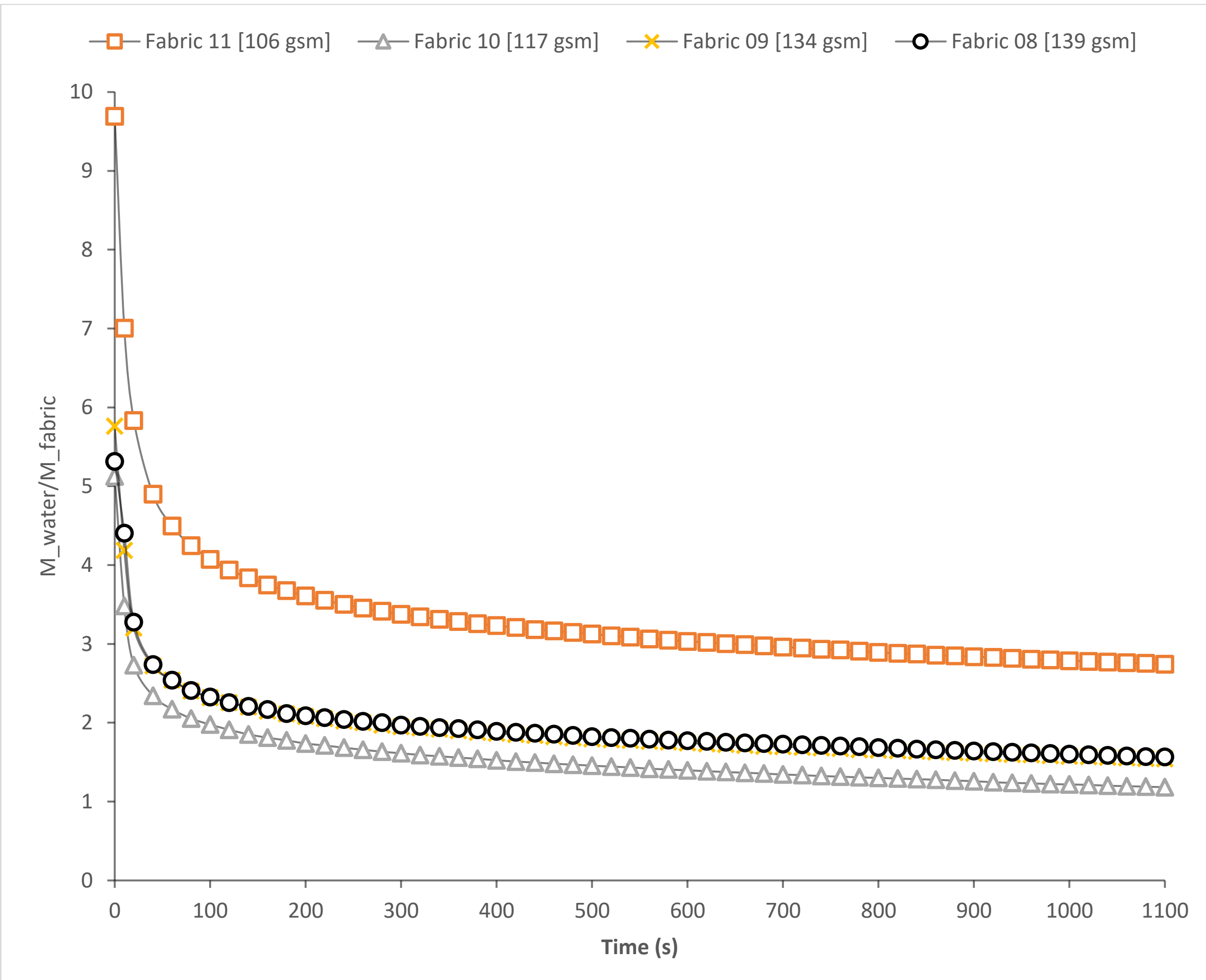

Figure 14: Normalized Water Content for Lightweight Woven Cotton Fabrics.

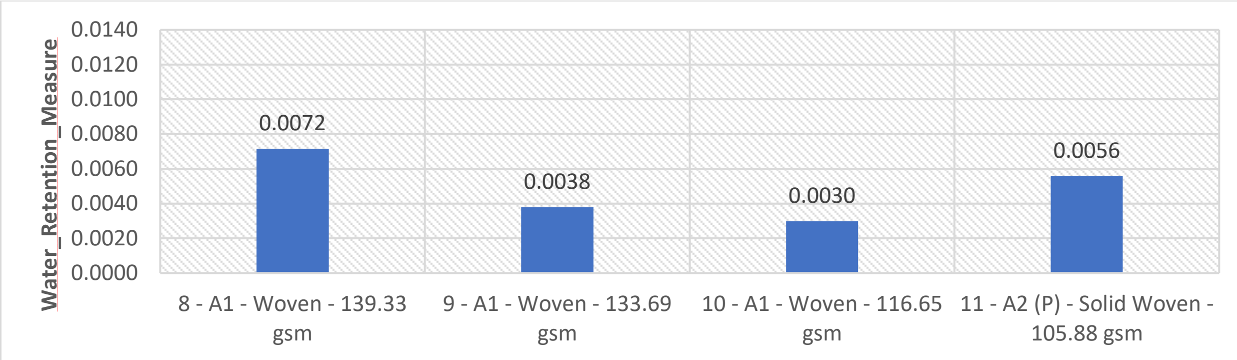

Figure 15: Water Retention Measure for Lightweight Woven 100% Cotton Fabrics.

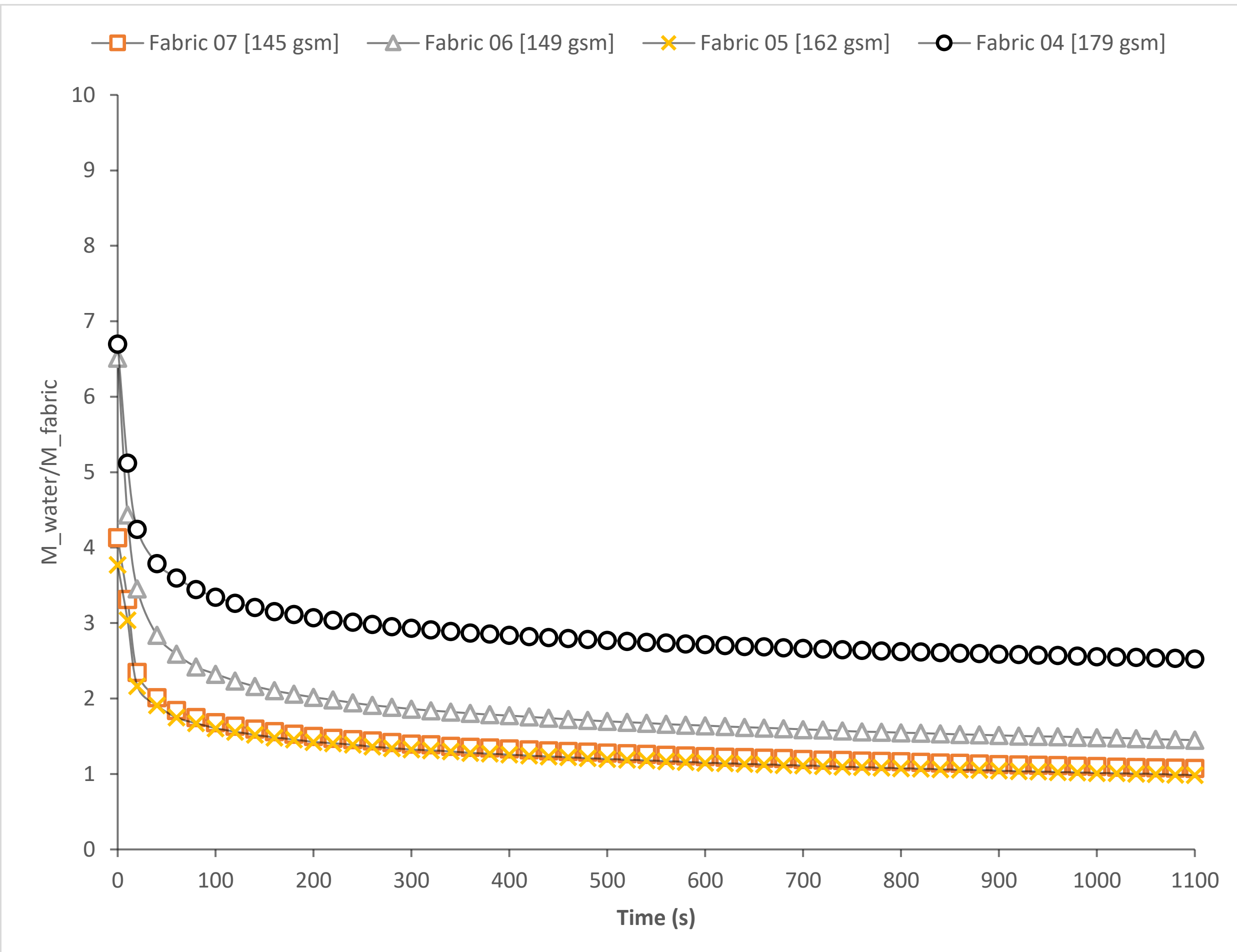

Figure 16: Normalized Water Content for Medium weight Woven Cotton Fabrics.

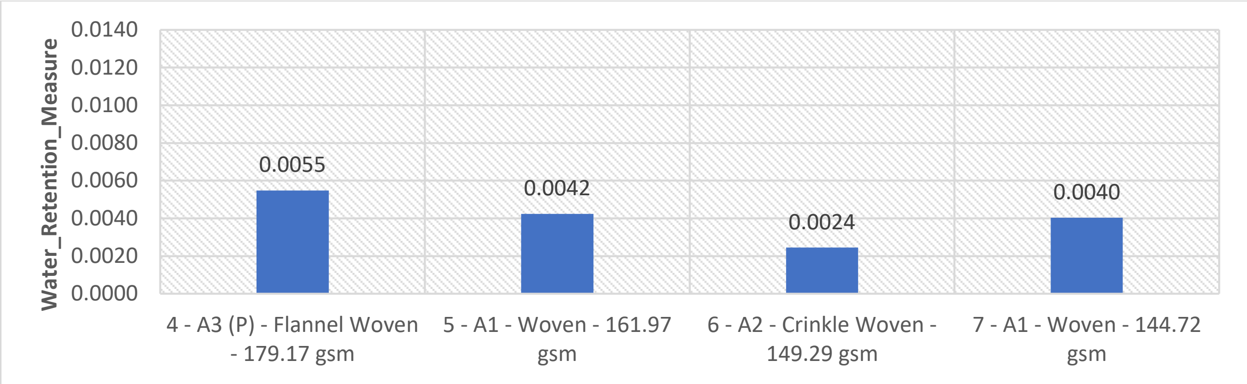

Figure 17: Water Retention Measure for Mediumweight Woven 100% Cotton Fabrics.

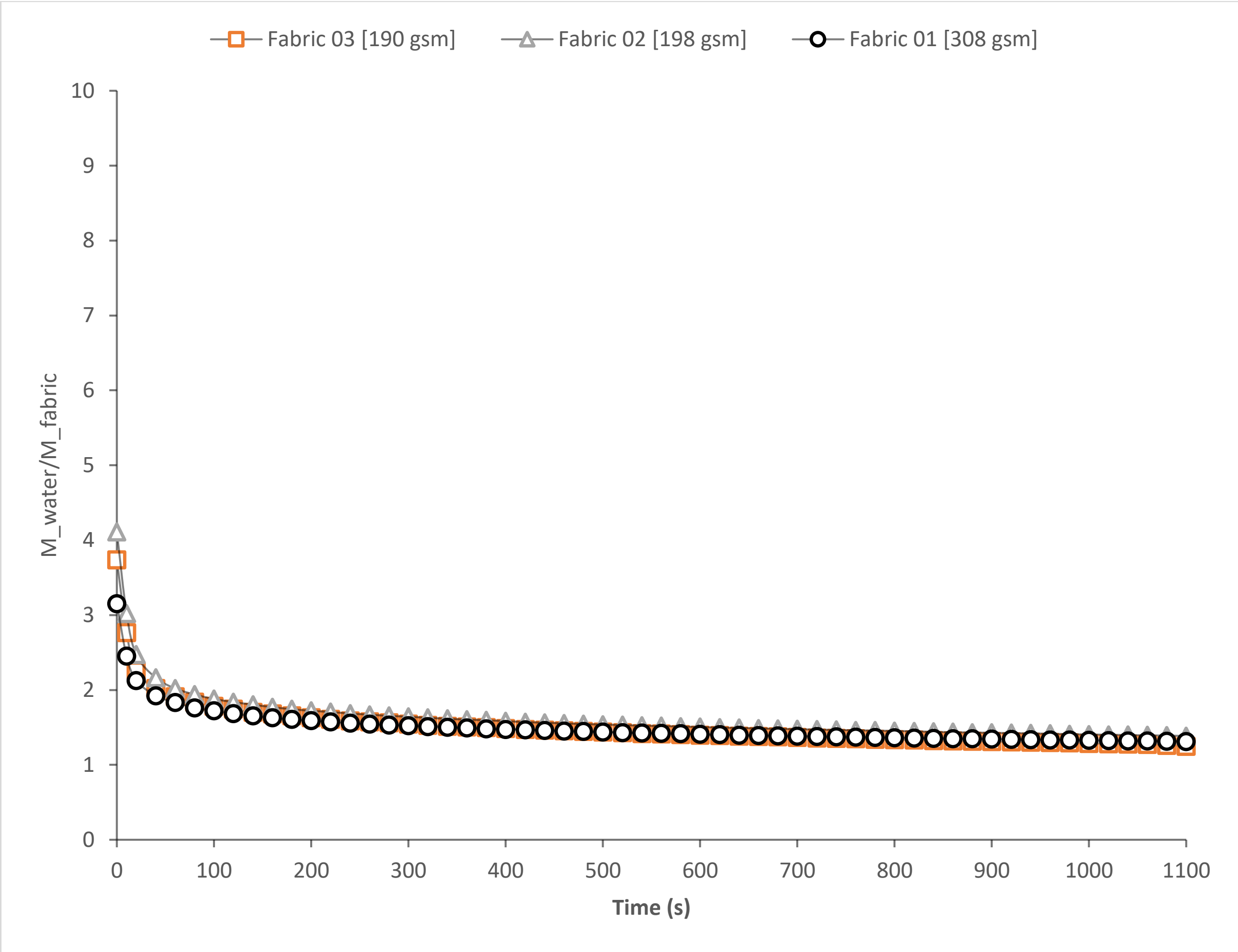

Figure 18: Normalized Water Content for Heavy weight Woven Cotton Fabrics.

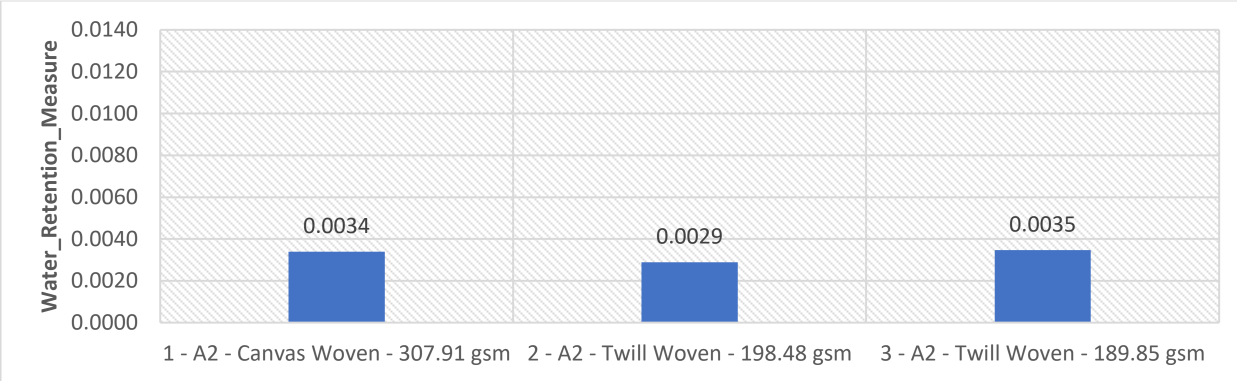

Figure 19: Water Retention Measure for Heavyweight Woven 100% Cotton Fabrics.

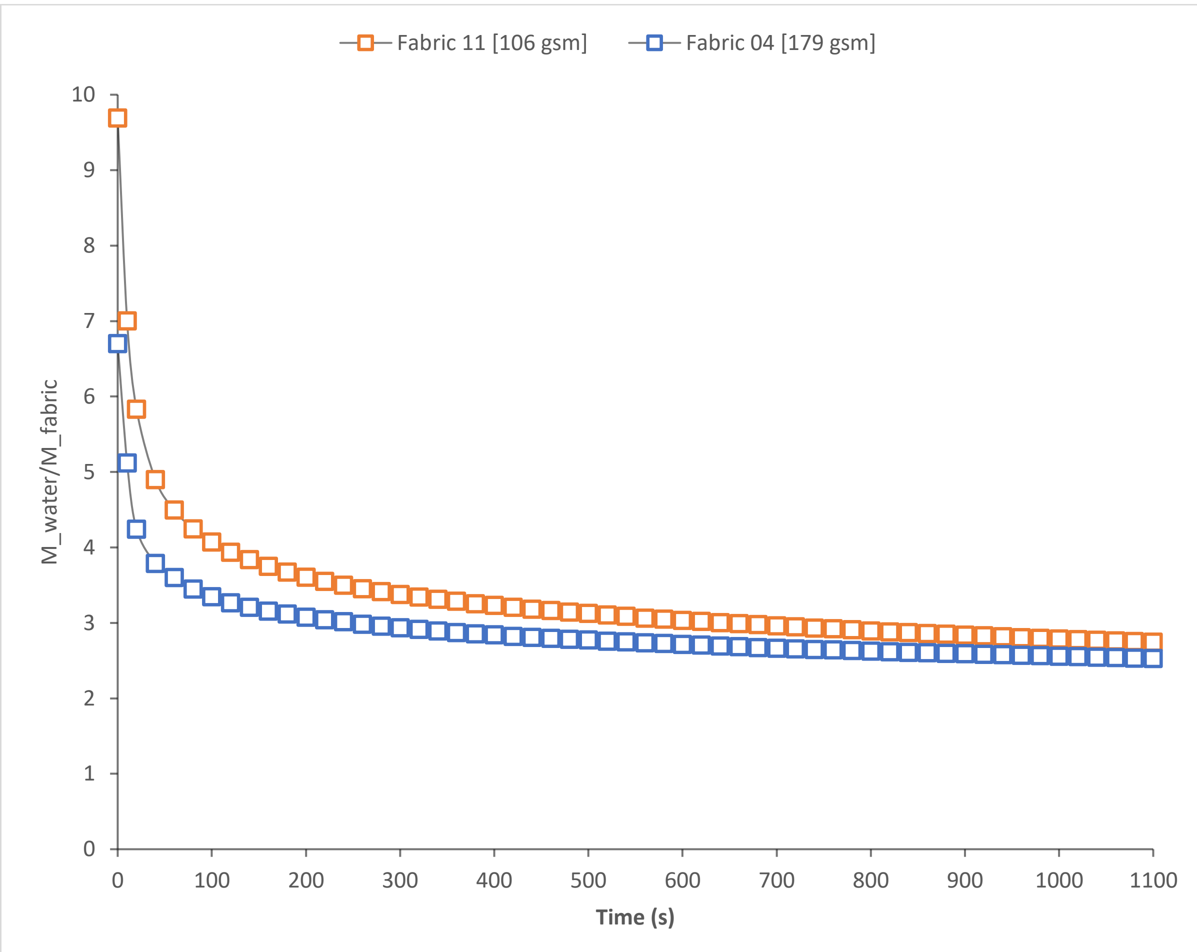

Figure 20: Comparison Between Fabric 11 and Fabric 04.

100% Polyester fabrics seen in Figure 21 have a NWC in the same regime as the 100% Cotton ones. Fabrics No. 12 and No. 13 have close results even with their big difference in density, their WRM (Figure 22) are positioned a little below the average. Fabric No. 14 have the worst performance on NWC but at the same time it has a very low density of 69 gsm, so it cannot be assured what is the factor responsible for its low water content, it could be the density, the yarn size, the free space in between the weaving, or the weaving pattern itself. But it can be identified as bad at water retainer.

Contrastingly, on WRM it has the highest value. It can be explained by considering its low water retention capacity and being low dense, which may limit and lower the saturation point, so the stabilization occurs smoothly although its end slope k1 is still quite pointing down, meaning that is still releasing water to a faster rate than the others.

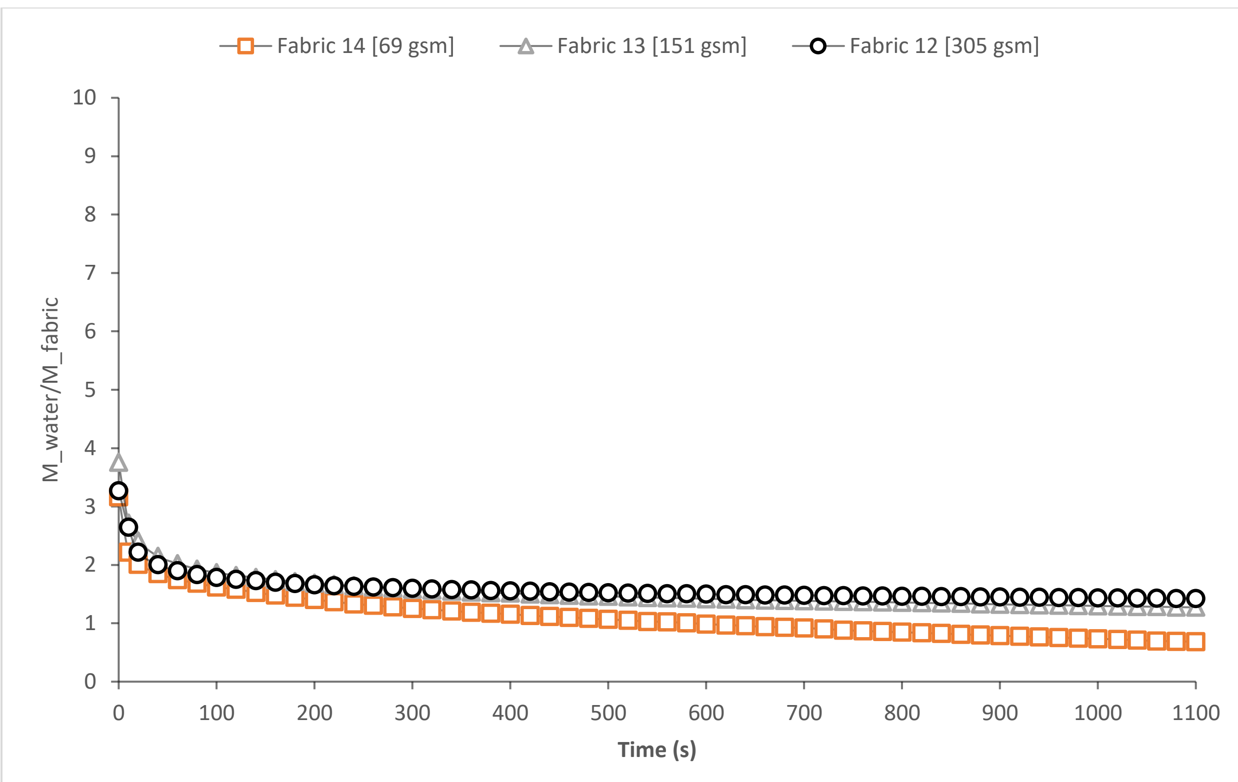

Figure 21: Normalized Water Content for Woven 100% Polyester Fabrics.

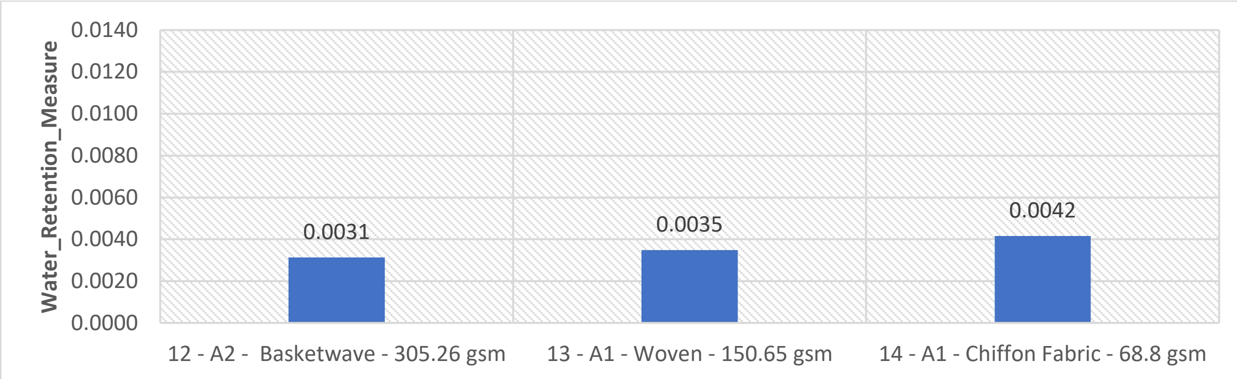

Figure 22: Water Retention Measure for Woven 100% Polyester Fabrics.

In addition to fabrics made of 100% of the same material, mixture compositions exist. Water retention performance evaluation has been done for these types of fabrics. In Figure 23, two of the fabrics have a composition of 65% Polyester and 35% Cotton while the rest have 80% Polyester and 20% Cotton. NWC results match very close, so it can be said that the mixture composition does not make a big difference. Fabric No. 16 showed poorer performance in the WRM (Figure 24), this can suggest that in this case an increment of polyester content makes the transition from saturation to a stable water release can be smoother. However, more investigation is needed to confirm this. Fabric No. 15 is interesting to mention because it stands out the rest, and a particularly of this weaving pattern is that have some bulks or accumulation of fabric distributed evenly over the surface, this is commercially called Seersucker Woven. This type of structure can be identified as good for water retention.

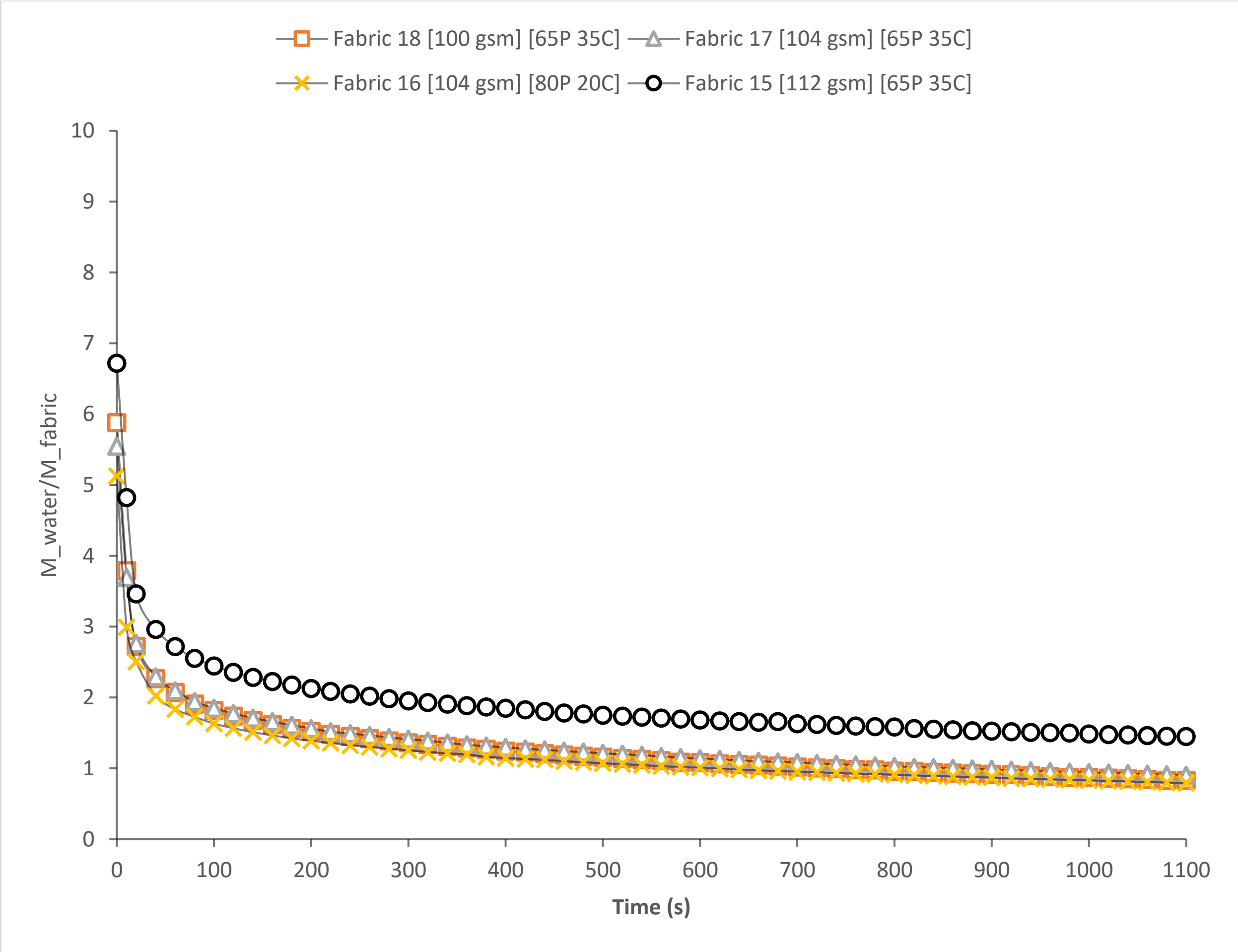

Figure 23: Normalized Water Content for Woven Fabric with Mixtures of Materials.

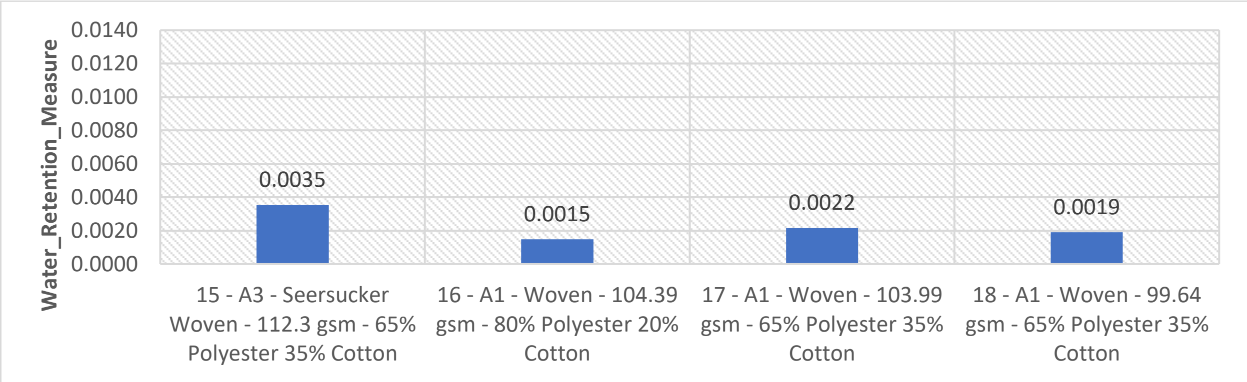

Figure 24: Water retention Measure for Woven Fabric with Mixtures of Materials.

Lightweight knitted fabrics on Figure 25 show a good Water Retention performance compared to the woven fabrics, specifically, Fabric No. 26 which have the Jersey Knit pattern. This is one of the most commercially common knit patterns that can be found. A double layer Jersey knit is also presented in this plot, both have similar performance with the difference that the double layer fabric drops more water content to reach to the same NWR value as the single layer fabric. When comparing the WRM from Fabric No. 26 (Figure 26) with the WRM of fabric No. 7, it can be observed that the first one performs 60% better, and this is an important comparison because both are the most common and simple weaving patters of their respective group: Single Jersey, and Simple Woven.

Mediumweight knitted fabrics compared in Figure 27 and Figure 28 also match in their performance. One is a Single Jersey fabric, and the other is a double layer combining a Warp knit on one side with a Rib knit on the other side. Moreover, heavyweight fabrics show very different performance under same conditions (Figure 29), this can be caused by how the weaving pattern influences the Water Retention process. Best performing fabrics have an Interlock knit and a Fleece knit, the first one consists in two layers interknitted, and the second one is made of simple knit with a generous amount of pilling on its surface. Besides from these characteristics, their structures are very consistent and can be identified as good for water retention. Fabric No. 23 performs well while its haves a double layer structure. Waffle Terry knit, and Pique knit from fabrics No. 19 and No. 20 respectively, can be identified a bad for water retention. Both have in common a B3 structure that can be related to its bad performance. When comparing with the WRM of Figure 30 both performances match, except for the Waffle Terry knit, which presents a similar case as the Fabric No. 11.

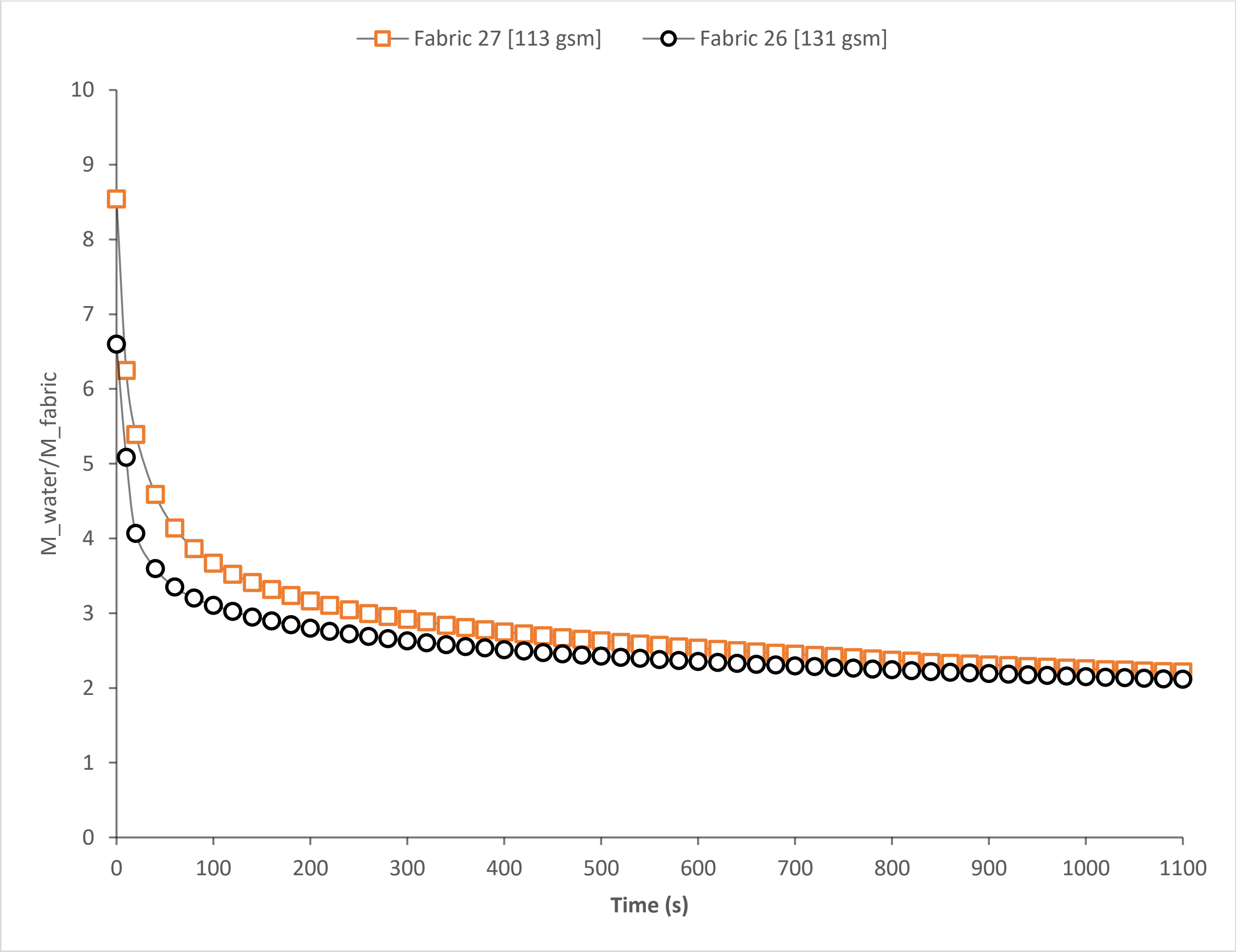

Figure 25: Normalized Water Content for Lightweight Knit Cotton Fabrics.

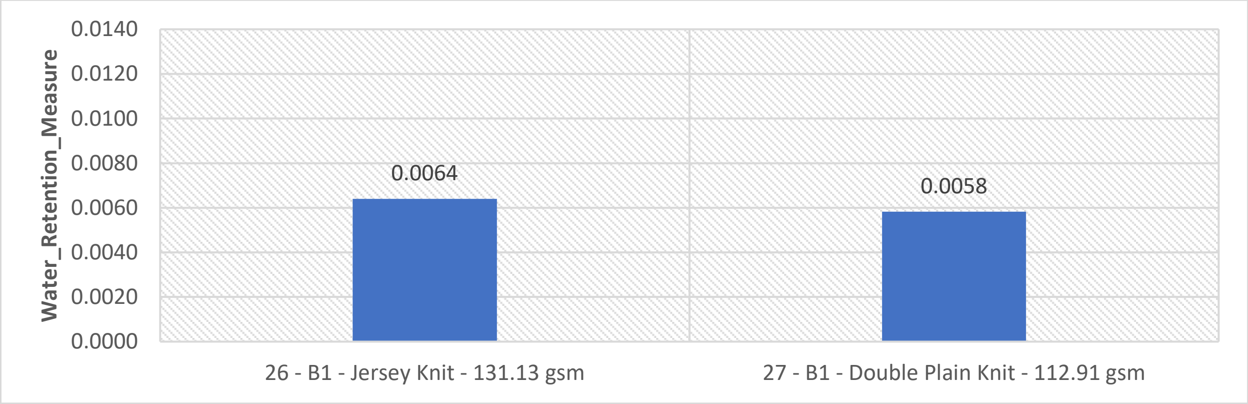

Figure 26: Water Retention Measure for Lightweight 100% Cotton Knitted Fabrics.

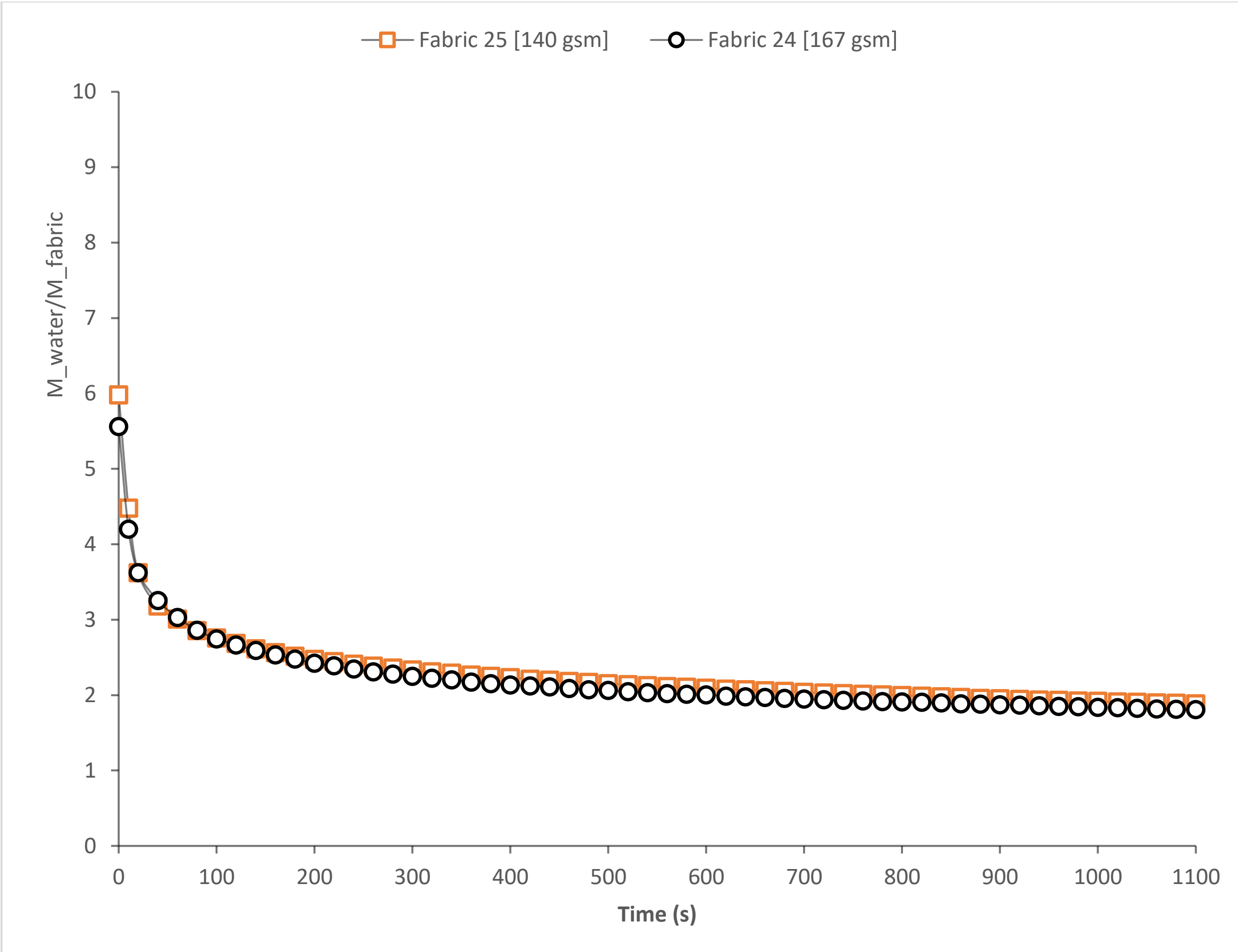

Figure 27: Normalized Water Content for Medium weight Knit Cotton Fabrics.

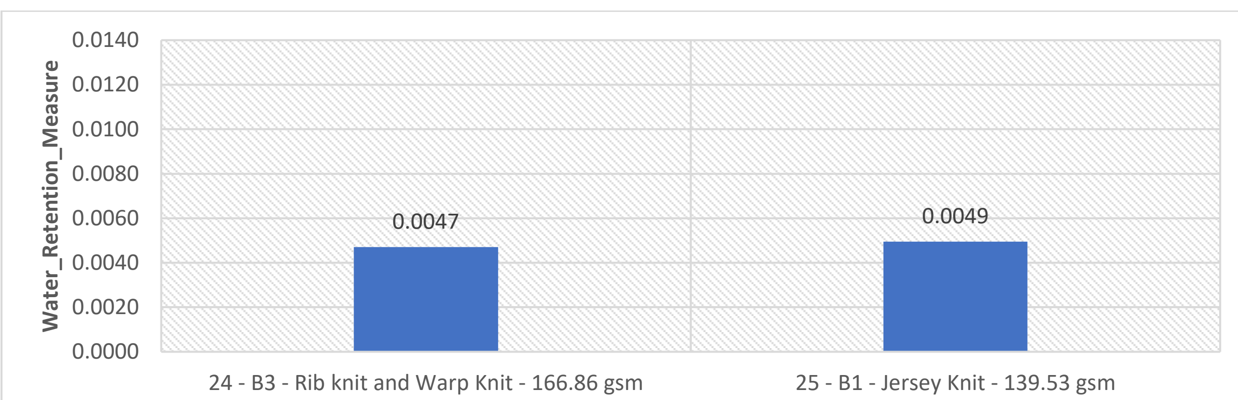

Figure 28: Water Retention Measure for Mediumweight 100% Cotton Knitted Fabrics.

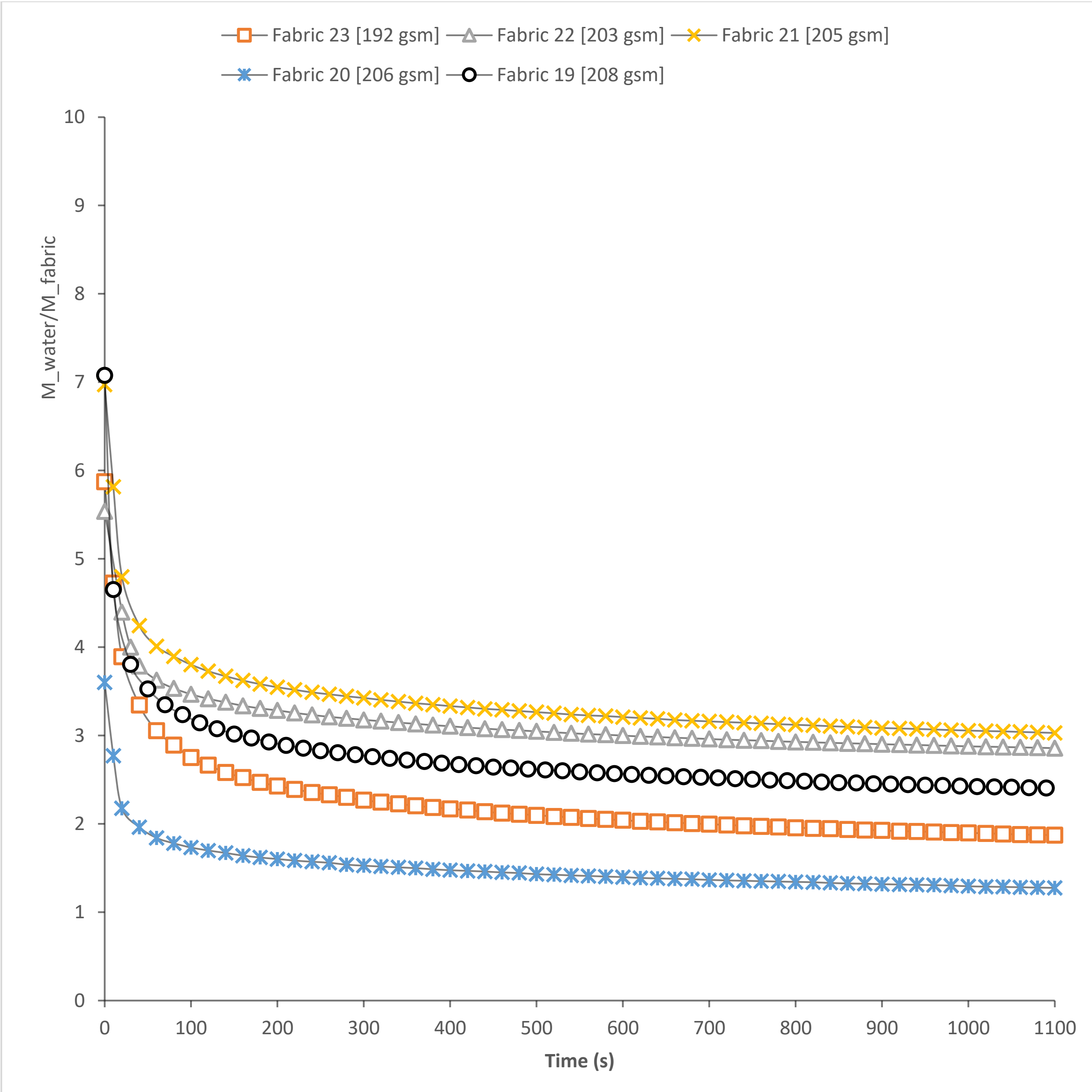

Figure 29: Normalized Water Content for Heavy weight Knit Cotton Fabrics.

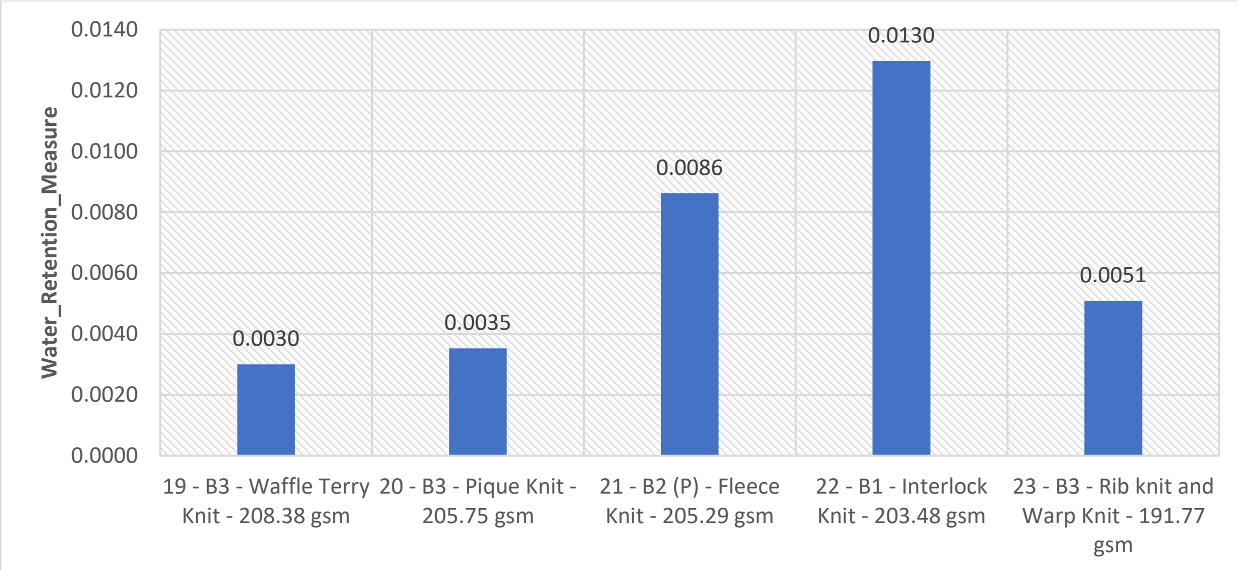

Figure 30: Water Retention Measure for Heavyweight 100% Cotton Knitted Fabrics.

100% Polyester knitted fabrics are presented in the Figure 31, good performance can be seen on lightweight and heavyweight fabrics, therefore it is evident that the density is not a dominant factor to determine the water retention. Scuba knit and Interlock knit have a WRM (Figure 32) higher than 0.01, meaning that their performance is exceptional, both patterns are made by two layers. Travel knit is also known as Tricot knit and have the highest WRM with one layer of fabric. All three have a low structure variability and can be classified as proficient for water retention. Pique knit have a B3 structure its water retention capacity is not as good as the rest. Comparison of Pique knit, and Interlock knit with their cotton versions was done (Figure 33). Fabrics No. 22 and No. 31 represent the cotton and the polyester versions of the interlock knit, it can be seen that the fabric identified as good for Water Retention (with low SVD), the cotton version is preferable because it largely surpass the polyester version performance. The opposite case happens with the high SVD Pique knit fabric; the polyester version performs better. With these results it can be concluded that while the fabric material does influence the Water Retention, this is not the dominant factor.

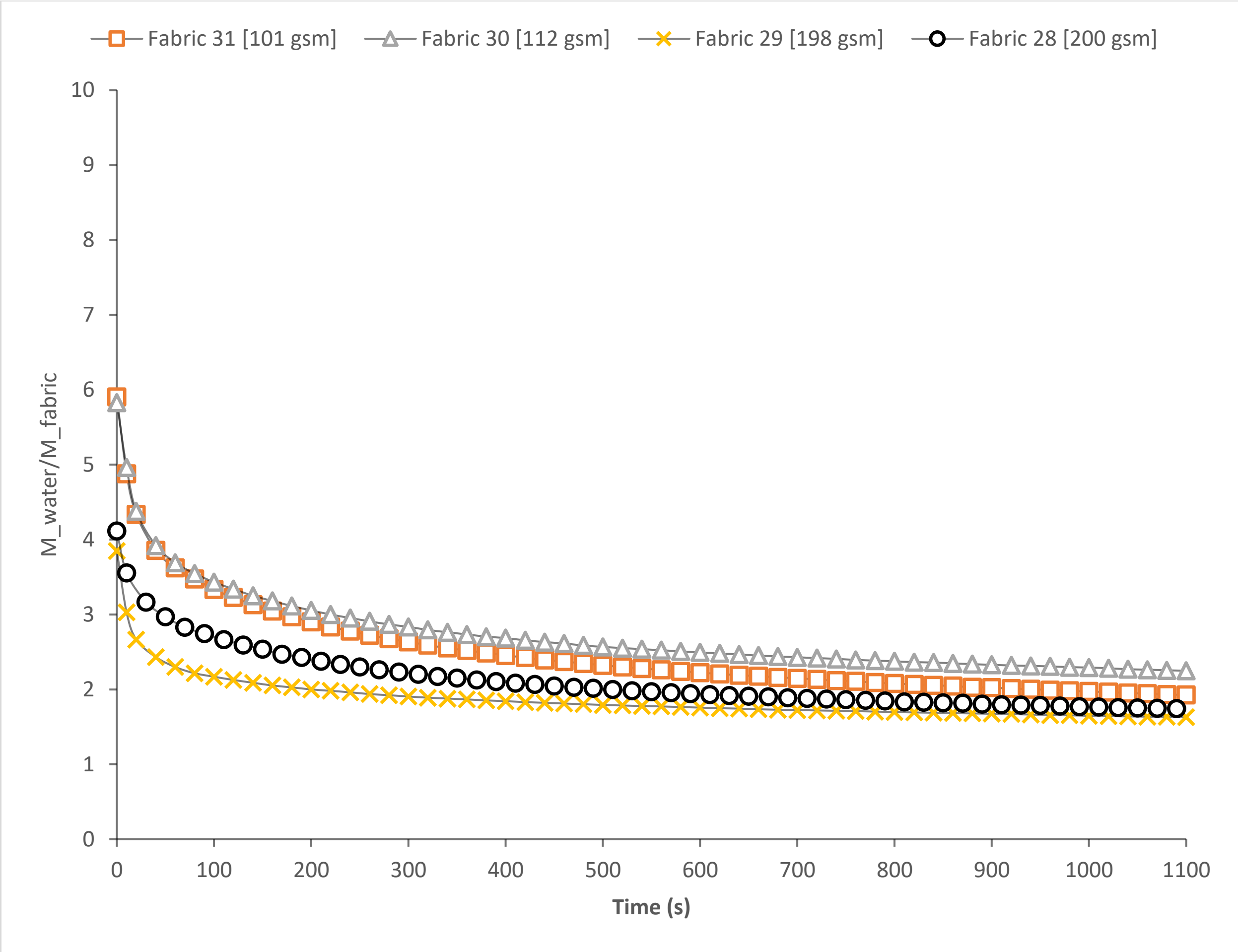

Figure 31: Normalized Water Content for Knit Polyester Fabrics.

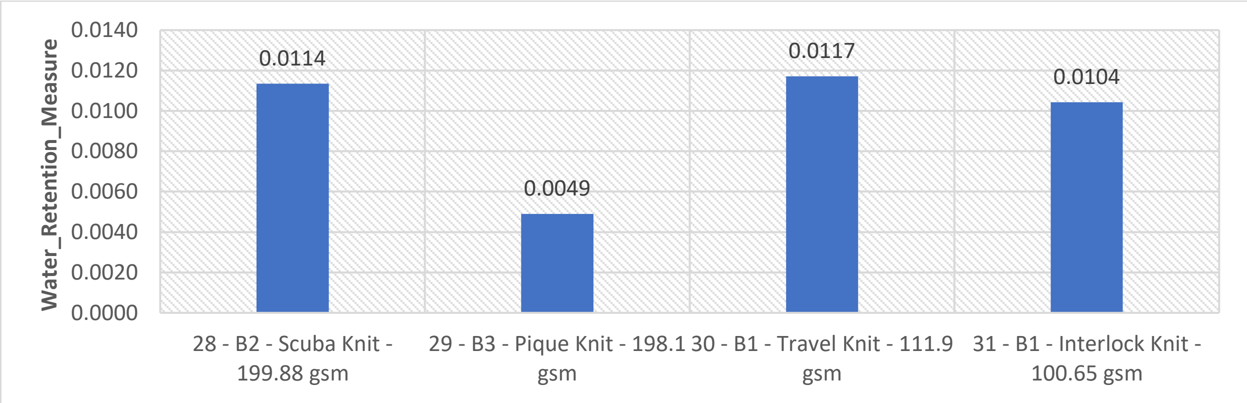

Figure 32: Water Retention Measure for 100% Polyester Knitted Fabrics.

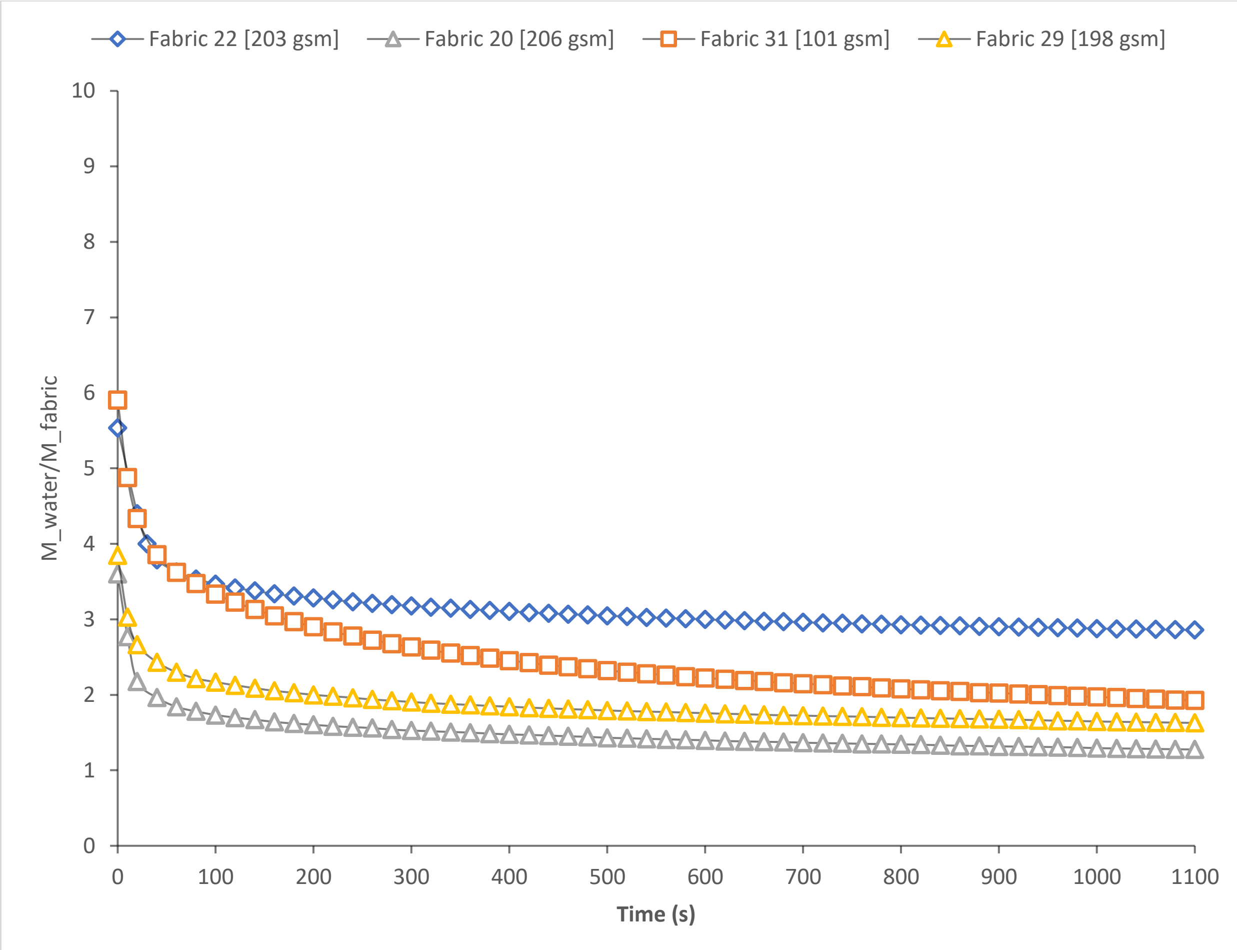

Figure 33: Normalized Water Retention Comparison on Cotton vs Polyester versions of the Pique and Interlock knitted fabrics.

Mixture knitted fabrics on Figure 34 are presented in two different plots according to the material composition, a) plot have fabrics composed of a majority of polyester, and b) shows fabrics with majority of cotton. Fabrics No. 33 and No. 32 performance is almost identical, have some difference in density but nearly same mixture materials content. These two stands as good for water retention. Talking about the NWC, fabrics with majority of polyester: No. 34 and No. 35, perform very similar than the ones with majority of cotton. But on WRM (Figure 35) they are way better than the rest.

Rib Knit Dryline and Liverpool Knit are their patterns. The first one is used on sport clothing to make the sweat transfer from the skin to the outer layer by wicking, so it's double layered. Liverpool knit have a texturized pebbled like side, making these fabrics to have an excellent performance. The remaining Rib knit, French Terry, and Purl knit perform on the average range of values (0.004 – 0.007 WRM). This shows that the knitted pattern is dominant over the material composition and over density for the Water Retention.

a)

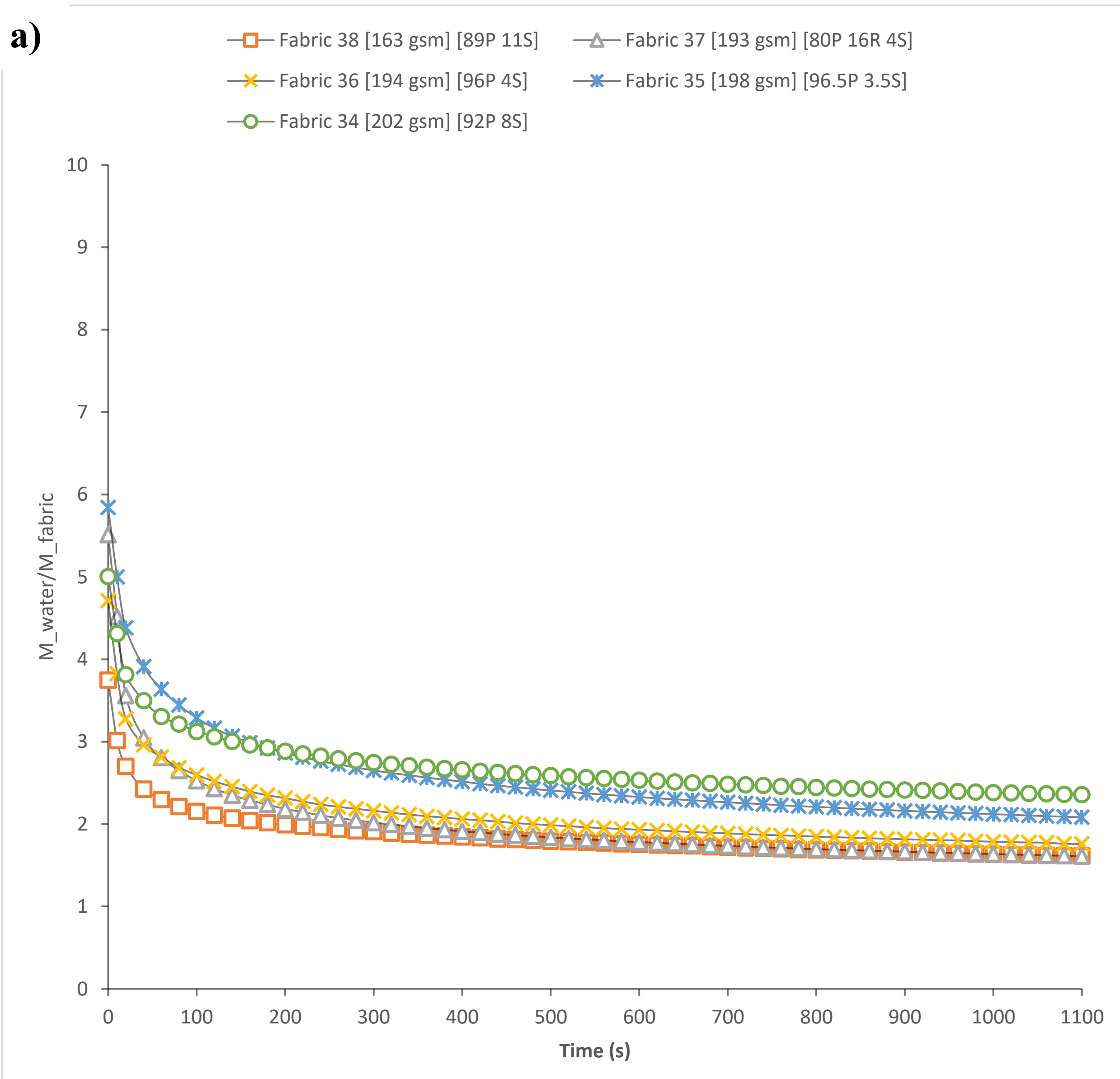

Figure 34: Normalized Water Content for Knit Mixture Fabrics. a) Major Polyester Fabrics. b) Major Cotton fabrics.

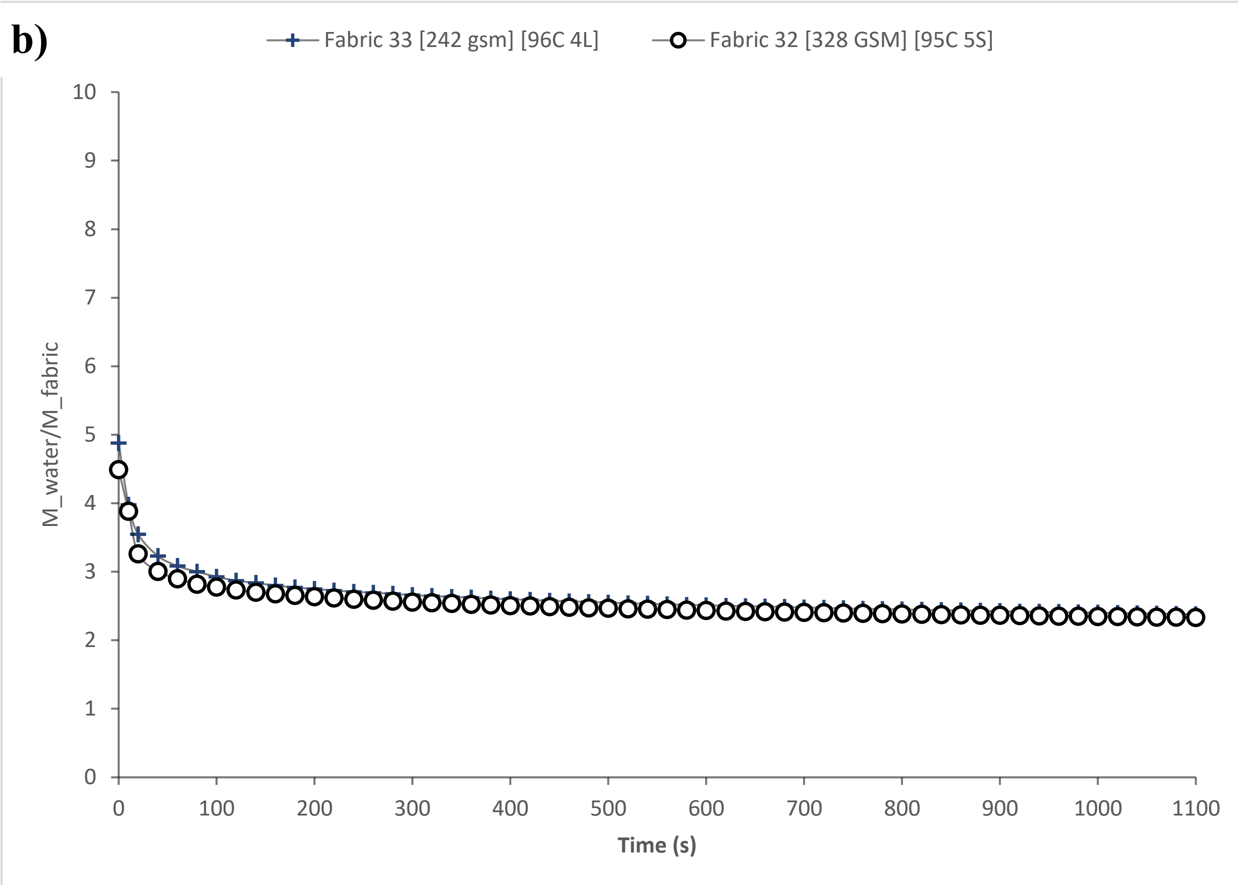

Figure 34, cont.

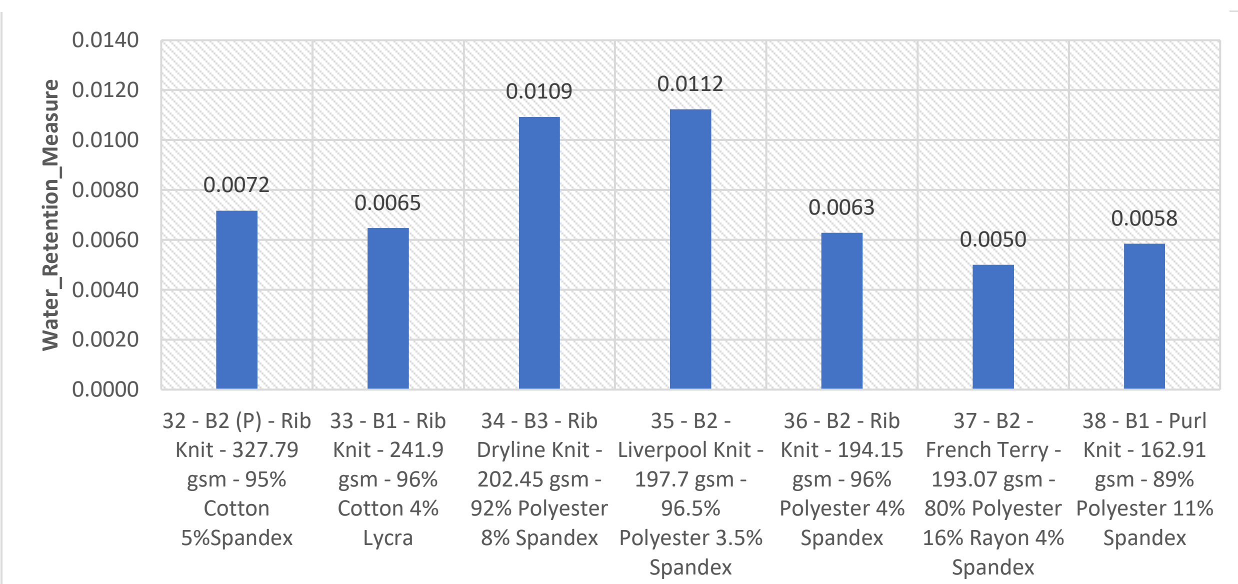

Figure 35: Water Retention Measure for Mixture Knitted Fabrics.

2.4.5 Findings

The density seems to do not influence the water retention performance. The dominant factor has been identified as the weaving pattern. Pilling have been found to improve the Water Retention significantly, Fleece and Gauze are the main woven patterns having it. A crinkle structure and a Chiffon fabric could worsen the water holding. Canvas, Basketweave, and Twill woven fabrics have not been identified as having better performance than a simple woven fabric. Seersucker fabric featuring fabric material accumulations can be identified as good retaining water. Among the woven fabrics analyzed, no evidence has been found that usage of 100% polyester or a mixture with cotton significantly change the performance.

Double layer single jersey did not show an improved performance. Other double layer fabrics performed proficiently good, these are the case of the Interlock and the Scuba knitted patterns. Both have a relatively constant structure, so water retention enhancing can be attributed to this characteristic. Very changing structure (high SVD) fabrics like the Pique knot and Waffle Terry knit showed a poor performance nearly like the woven fabrics. This can be identified as a feature that can worsen the water holding. Travel knit is identified as a very good water retainer along with the Fleece knit which have a lot of pilling. Liverpool knit features a Texturized layer. The Rib knit found commercially can vary by a lot. Dryline Rib knit have a two-layer structure and performed very well. French Terry and Purl knit operate in the average values. A comparison between cotton and polyester versions of Pique and Interlocked knit revealed interesting findings. The Cotton interlocked version is the best fabric overall to hold water, and its polyester version is far below that performance. The material is not the main factor to determine the Water Retention capability, rather, the weaving pattern is dominant.

2.5 Wicking Testing

The humidifier fabrics are wet by the overtopping system, so the water can flow through the fabrics surface, create a film, and enhance the humidifying process of the air passing along its length. The actual HDH desalination system is meant to be deployed floating on the ocean surface. Days of calm waters in where waves may be not common are expected to occur, so in that situation, the wetting by overtopping may not happen, rather, as the fabrics are partially submerged, capillary wicking will be the main wetting mechanism. This makes the water film on the fabric surface to do not exist. For that reason, it is important to better understand the wicking behavior of each of the fabrics and learn what characteristics improves the wicking, so selected fabrics could improve the performance of the humidifier device in calm days.

2.5.1 Setup

Testing setup consists of an acrylic frame with two horizontal holders maintaining the fabric firm without wrinkles without tension it. This frame holding the fabric is submerged in a water container and a ruler scale with a heavy base is placed in front of the fabric. The container is filled with a water pump to the mark of 3.5 inches on the ruler. The whole setup is placed on a custom-made lightbox being illuminated with two light bulbs; the purpose is to better see the wetting line thorough the transparent ruler while a camera records this process. Figure 36 shows the diagram of the setup with the parts previously mentioned marked, and the submerged length of the fabric is highlighted on b). Figure 37 displays a photo of the actual setup used for testing.

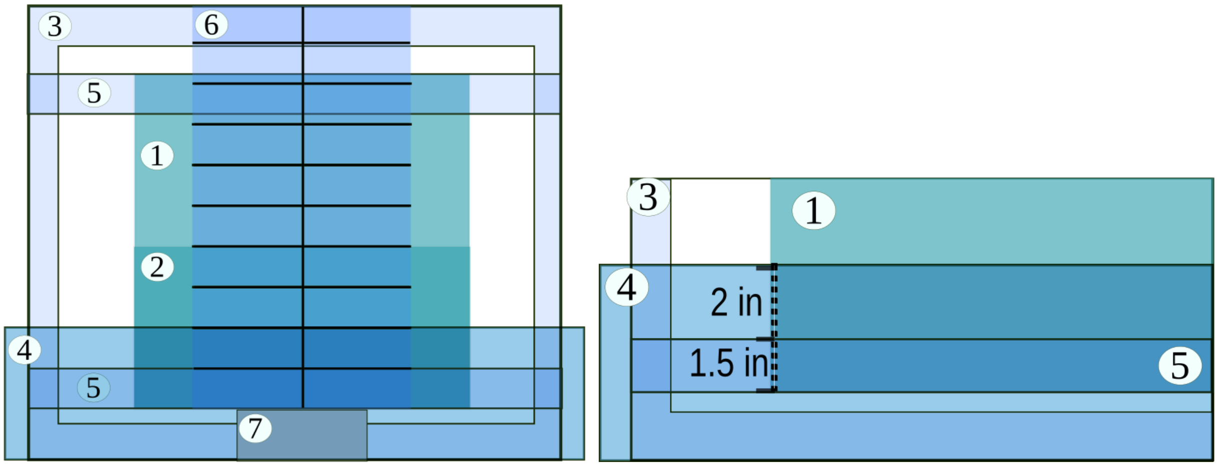

Figure 36: Front view of the of Wicking setup. 1. Dry portion of the fabric, 2. Wet portion of the fabric, 3. Frame, 4. Water container, 5. Fabric holders, 6. Ruler, 7. Ruler base.

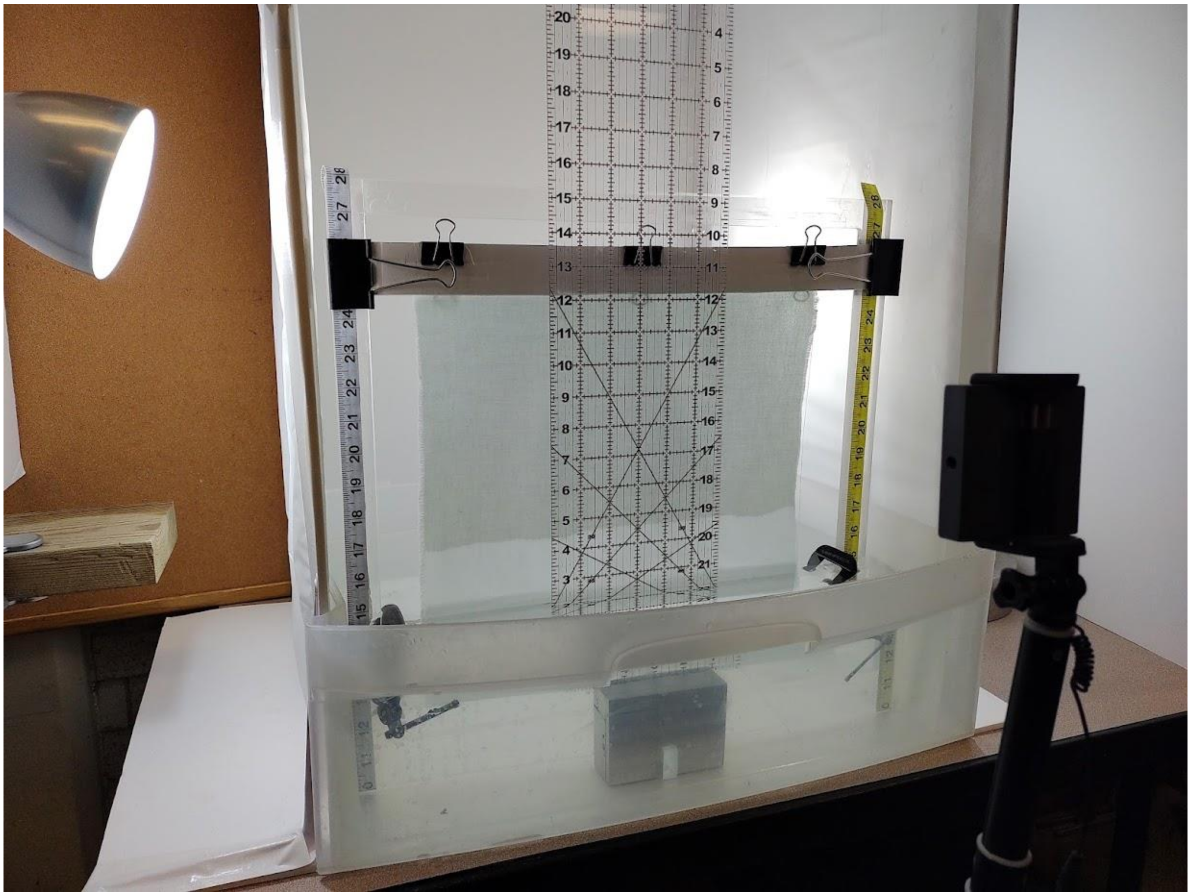
Figure 37: Photo of the wicking setup inside a lightbox with two lamps placed on the sides.

2.5.2 Parameters

Constant parameters were defined to make the testing conditions even. The amount of fabric length submerged is always 3.5 inches, which results in an approximate submerged area of 49 in^2. Tap water was used at ambient temperature. All the testing were performed inside an air-conditioned laboratory at 20.8 °C ±5°C, and a of Relative Humidity 52.5% RH ±7.5%. Wrinkles on the fabric were avoided to not let them influence the wicking process.

The testing preparation starts by attaching the fabric to the dry frame and place it into the water contained at a very low water level, so the wicking does not start. The frame and the ruler are adjusted in the field of view of the camera that records the wicking process. Ruler is placed separated by a small gap to the fabric to avoid the wet fabric to stick to it. Due to the height of the setup, the camera is placed facing down at small angle, so it records the entire process from a bottom-to-top perspective, this causes the initial reading to be different from the actual value, but as the angulation is constant, so this momentary mismatch is later fixed in the data processing. A submersible water pump raises the water level on the container by a rate of 25 l/min until the 3.5 in mark is under the water, then the testing time begins. Each test is run for 60 minutes and repeated three times starting always from a dry fabric. Depending on the fabric color and thickness it may require or not require turning on the lights. Two commercial LED daylight bulbs of 1200 Lumen each placed on the sides. Also, because of the weaving pattern, some fabrics have sides in which the water wicking line can be appreciated better. So, special conditions were determined for each fabric.

In the begging the wicking velocity is fast but later it gets slowed significantly. Variable time interval was defined to take the reading on the ruler. Readings were recorded from the video every 1 second for the first 10 seconds, every 5 seconds for the next 20 seconds, every 10 seconds for the next 30 seconds, every 20 seconds for the next 2 minutes, every 30 seconds for the next 2 minutes, every minute for the following 5 minutes, every 2 minutes for the subsequent 10 minutes, and finally every 2:30 minutes for the last 40 minutes. This rhythm of data collection adjusts to the wicking velocity of most of the fabrics.

2.5.3 Results

The average wicking velocity of each of the fabrics was determined: the total traveled distance was divided by 3600 seconds for most fabrics. In case of fabrics with a very fast wicking, the time used was the required to get to the maximum height that could be recorded with the setup. Wicking velocity is not constant through all the wicking process because the capillary force making the moisture to climb over the fabric inside and outside yarns changes depending on the height rather than changing with the time. This is caused by the gravity force and the exposure of more wet fabric surface to the ambient, so evaporation starts to occur faster until a balance between wicking and evaporation is reached. An average velocity does not describe the full wicking process, but it is useful to characterize the fabrics wicking performance. The wicking velocities are presented in Table 6.

Table 6: Wicking Velocity Results for each fabric.

No.	Weaving Pattern	Material	gsm	Structure Variation Degree	Wicking Velocity (mm/min)
1	Canvas Woven	100% Cotton	307.9	A2	**2.25**
2	Twill Woven	100% Cotton	198.5	A2	**1.99**
3	Twill Woven	100% Cotton	189.9	A2	**2.68**
4	Flannel Woven	100% Cotton	179.2	A3 (Pilling)	**3.40**
5	Woven	100% Cotton	162.0	A1	**1.08**
6	Crinkle Woven	100% Cotton	149.3	A2	**0.85**
7	Woven	100% Cotton	144.7	A1	**2.22**
8	Woven	100% Cotton	139.3	A1	**0.51**
9	Woven	100% Cotton	133.7	A1	**0.95**

Table 6, cont.

No.	Weaving Pattern	Material	gsm	SVD	Wicking Velocity (mm/min)
10	Woven	100% Cotton	116.7	A1	**2.04**
11	Gauze Woven	100% Cotton	105.9	A2 (Pilling)	**1.85**
12	Basketweave	100% Polyester	305.3	A2	**3.33**
13	Woven	100% Polyester	150.7	A1	**0.51**
14	Chiffon Fabric	100% Polyester	68.8	A1	**0.48**
15	Seersucker Woven	65% Polyester 35% Cotton	112.3	A3	**1.03**
16	Woven	80% Polyester 20% Cotton	104.4	A1	**1.83**
17	Woven	65% Polyester 35% Cotton	104.0	A1	**1.64**
18	Woven	65% Polyester 35% Cotton	99.6	A1	**2.22**
19	Waffle Terry Knit	100% Cotton	208.4	B3	**3.87**
20	Pique Knit	100% Cotton	205.8	B3	**2.93**
21	Fleece Knit	100% Cotton	205.3	B2 (Pilling)	**2.22**
22	Interlock Knit	100% Cotton	203.5	B1	**2.30**
23	Rib knit and Warp Knit	100% Cotton	191.8	B3	**1.14**
24	Rib knit and Warp Knit	100% Cotton	166.9	B3	**1.40**
25	Jersey Knit	100% Cotton	139.5	B1	**2.83**
26	Jersey Knit	100% Cotton	131.1	B1	**2.59**
27	Double Plain Knit	100% Cotton	112.9	B1	**0.81**
28	Scuba Knit	100% Polyester	199.9	B2	**0.71**
29	Pique Knit	100% Polyester	198.1	B3	**3.44**
30	Travel Knit	100% Polyester	111.9	B1	**0.23**
31	Interlock Knit	100% Polyester	100.7	B1	**0.53**
32	Rib Knit	95% Cotton 5%Spandex	327.8	B2 (Pilling)	**2.67**
33	Rib Knit	96% Cotton 4% Lycra	241.9	B1	**7.16**
34	Rib Dryline Knit	92% Polyester 8% Spandex	202.5	B3	**2.62**
35	Liverpool Knit	96.5% Polyester 3.5% Spandex	197.7	B2	**0.25**
36	Rib Knit	96% Polyester 4% Spandex	194.2	B2	**1.19**
37	French Terry	80% Polyester 16% Rayon 4% Spandex	193.1	B2	**1.59**
38	Purl Knit	89% Polyester 11% Spandex	162.9	B1	**2.78**

2.5.4 Discussion

Fabrics in Figure 38 are simple woven except for No. 11, which is Gauze Woven with Pilling, its wicking velocity is close to the Fabric No. 10 velocity of 2 mm/min. Fabrics No. 08 and No. 09 do perform worse under similar conditions. This reduction in velocity can be attributed to their dyed yarns, so this characteristic can be identified to interfere in the wicking process and then create a slow velocity.

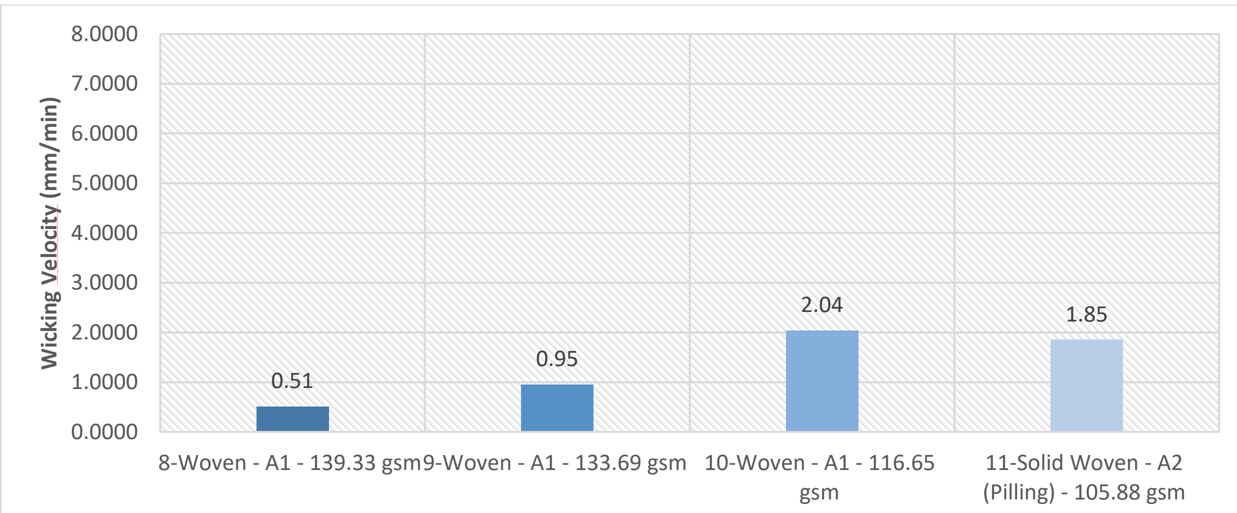

Figure 38: Wicking Velocity for Lightweight 100% Cotton Woven Fabrics.

Mediumweight cotton woven fabrics in Figure 39 displays the Flannel fabric having the highest wicking velocity, the particularity of this fabric is that it has a generous amount of Pilling. Regular simple woven Fabric No. 7 stays on the average velocity values of around 2 mm/min. Fabric No. 5 velocity can be considered as slow, the reason can be due to it is a printed fabric, so that affect wicking negatively. And even slower is the fabric No. 6, its unique characteristic is its crinkle structure, which was already identified as bad for water retention, now it can be said that it also reduces the wicking velocity.

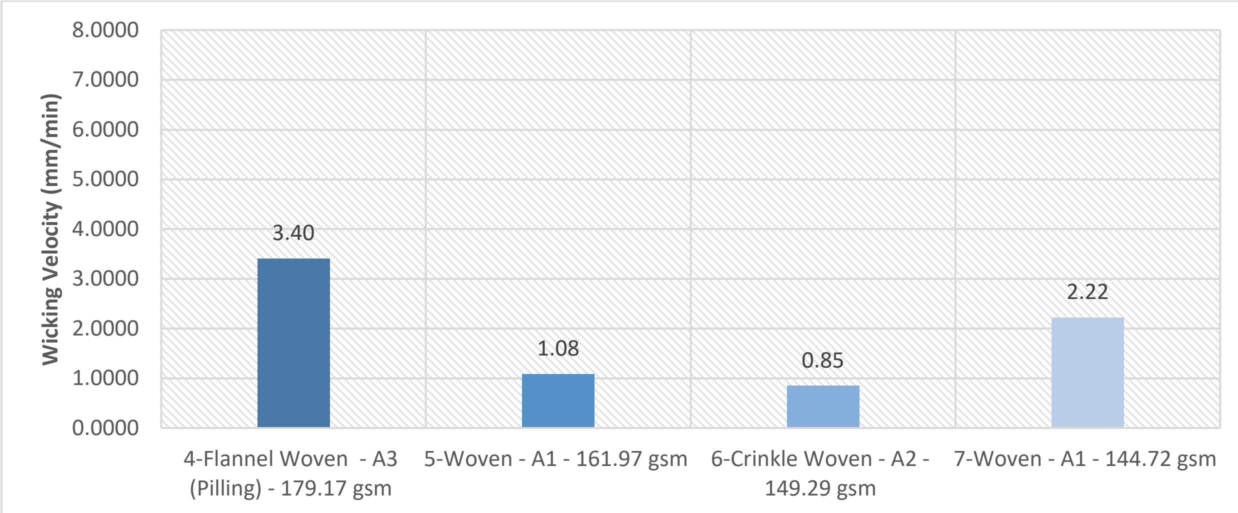

Figure 39: Wicking Velocity for Mediumweight 100% Cotton Woven Fabrics.

Velocities of the fabrics in Figure 40 can be classified as in the average, they are two different patterns: the Canvas and the Twill woven. Both have a SVD of A2. Even that their patterns and densities are different, performance closely matches, meaning that those patterns do not accelerate the wicking velocity in overall, and the density until this point seems to do not have an influence. Twill woven from Fabric No. 3 is better for apparently having a higher number of Threads per inch than the rest of the fabrics. However, more evidence is needed to be able to confirm that.

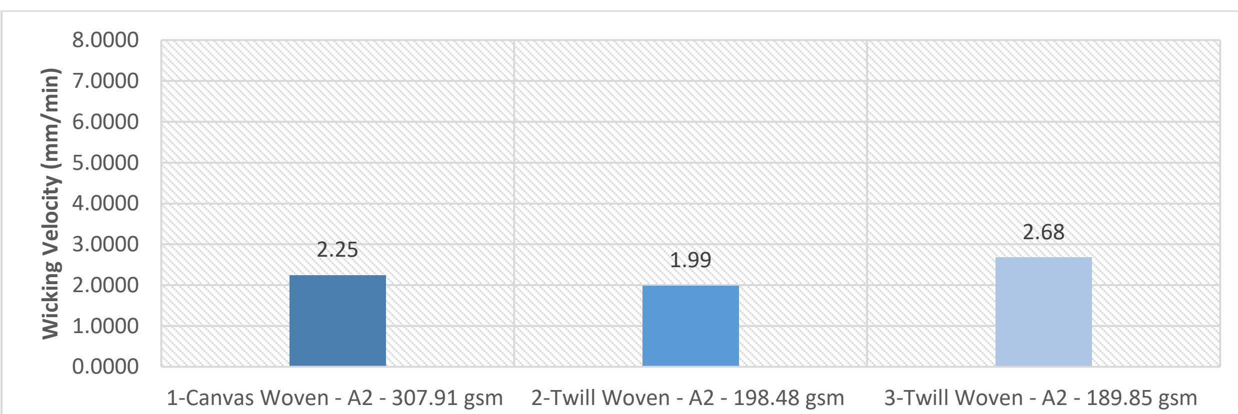

Figure 40: Wicking Velocity for Heavyweight 100% Cotton Woven Fabrics.

Fabric No. 13 on Figure 41 have a very slow velocity and is in similar condition than fabric No. 07 which is the 100% Cotton version, therefore it can be said that for wicking, cotton material on a woven fabric is preferable. Chiffon fabric is not good retaining water, and it also have a slow wicking. Basketweave 100% polyester fabric have a very high wicking speed, this woven pattern can be set as beneficial for wicking.

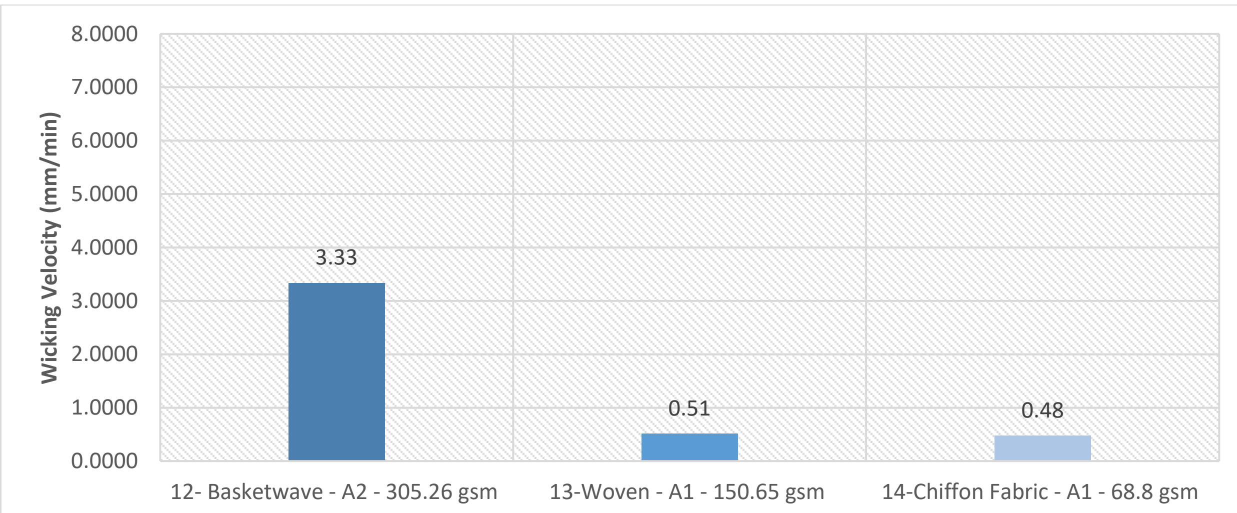

Figure 41: Wicking Velocity for 100% Polyester Woven Fabrics.

Seersucker woven pattern shows a slow wicking velocity in Figure 42, its accumulation of fabric of the surface could not benefit the wicking velocity. Fabrics No. 16, No. 17, and No. 18 are simple woven but with some differences in the mixture cotton-polyester composition, no clear trend shows a relationship between having more or less cotton content and the wicking velocity, its velocities are close to the 100% cotton version, but they don't are as low as the 100% polyester version, so this may suggest that some percentage of the mixture has to be cotton to have a better wicking velocity, but this needs more investigation.

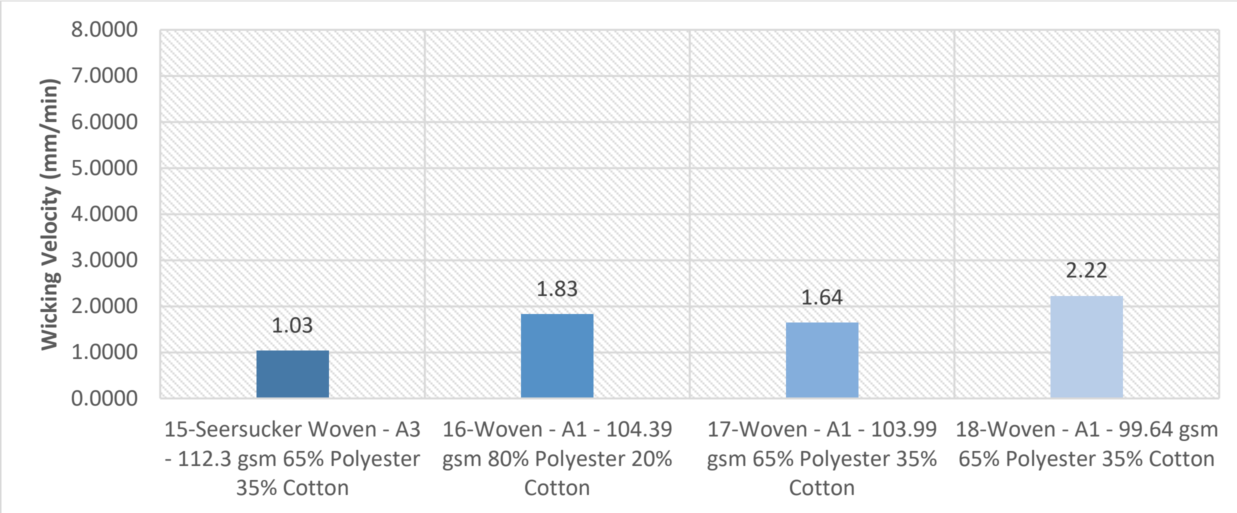

Figure 42: Wicking Velocity for Mixture Woven Fabrics.

Similar versions of a Simple Jersey knit are presented in the Figure 43 and Figure 44, this fabric have higher velocity than regular simple woven fabric. Also, double layer fabrics are being compared in those plots, both are slower than regular Single Jersey, this can suggest that having a double layer could slow down the wicking, and it can be explained due to blockage of the free air spaces between the yarns by the opposing layer.

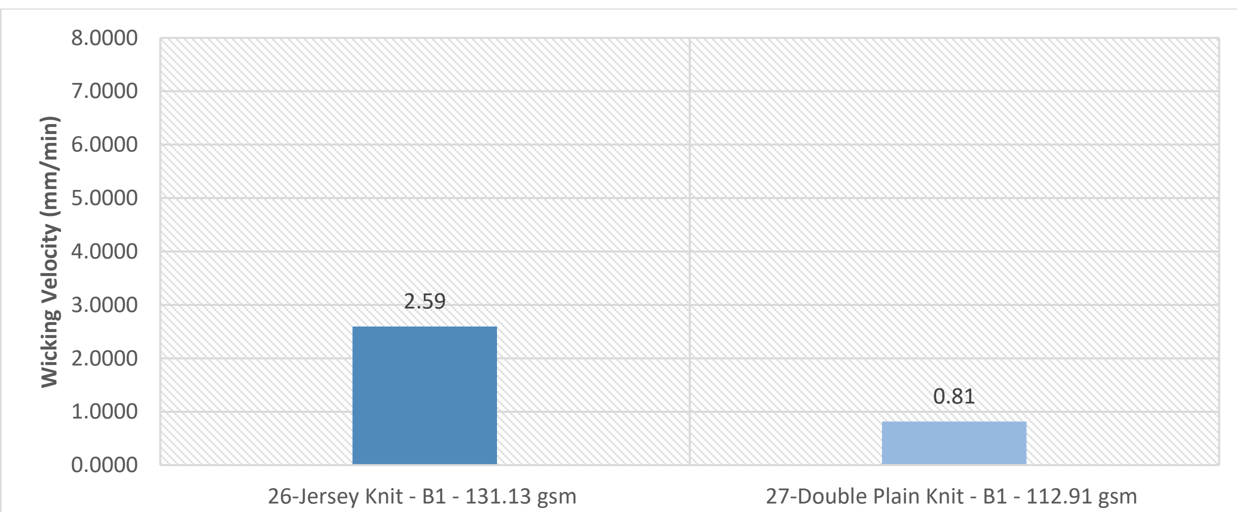

Figure 43: Wicking Velocity for Lightweight 100% Cotton Knitted Fabrics.

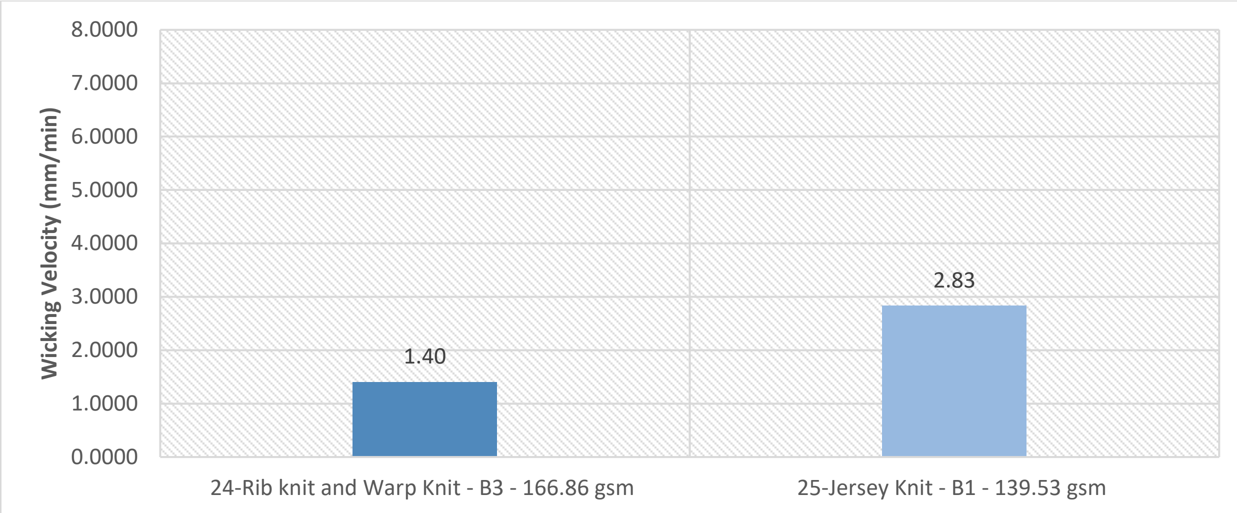

Figure 44: Wicking Velocity for Mediumweight 100% Cotton Knitted Fabrics.

Fabrics with high SVD of B3 as the Waffle Terry and Pique knit are displayed in the Figure 45, these have the highest wicking velocity, while Fleece knit and Interlock knit having an SVD of B2 have a velocity near the average values of 2 mm/min, therefore it can be identified that a high SVD benefits the wicking more than having pilling or a interlock structure. Fabric No. 23 having double layers presents a very low velocity.

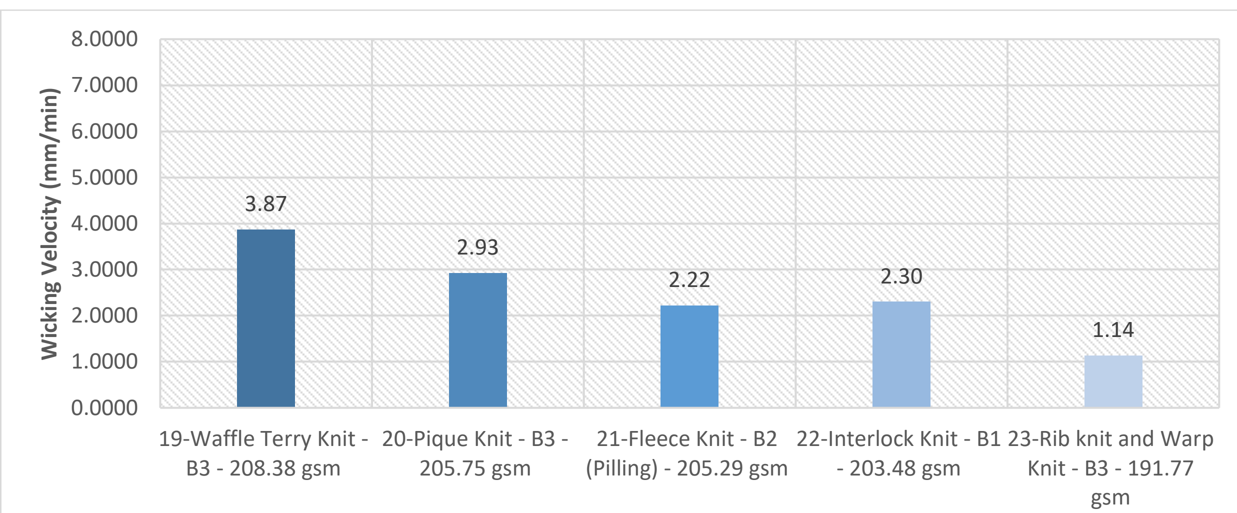

Figure 45: Wicking Velocity for Heavyweight 100% Cotton Knitted Fabrics.

Material influence on the wicking process can be observed in the Figure 46, Scuba knit is a double layer fabric, so this condition and having 100% polyester composition lead to a low wicking speed of 0.7 mm/min. Travel knit is not double layer but is a tricot knit pattern and it can be identified as not good for wicking. Interlocked polyester version fabric showed a poorer performance than its cotton version. An interesting case happens with the Pique knit in which the polyester version is faster by 0.5 mm/min than the cotton version, this can be due to versions of the Pique knits are not exactly the same.

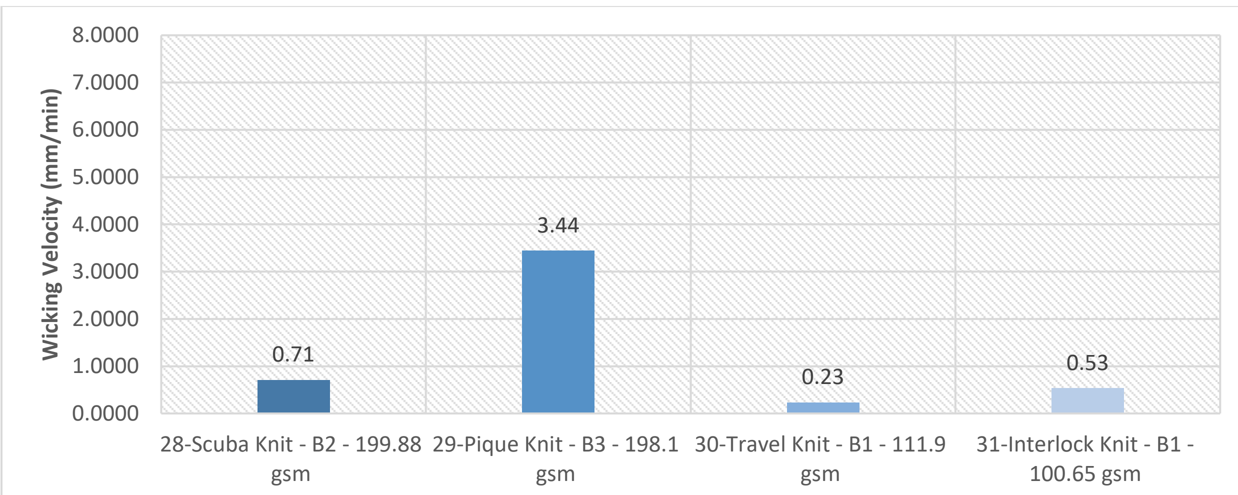

Figure 46: Wicking Velocity for 100% Polyester Knitted Fabrics.

The first two fabrics from left to right on Figure 47 are both 1x1 Rib knits, but the first one has a generous amount of pilling over its surface and the other don't. Even that, the one without pilling performs exceptionally good having the highest velocity of all the tested fabrics so far. A particularity of this Fabric No. 33 is its color, it is commercially named Heather grey, and this specific color can be seen as having various shades of gray in a non-uniform way as it can be observed in the photos of . All the fabrics are conformed by yarns, but these yarns instead of being dyed or printed, are conformed by different fibers of the same material (in this case yarns are of polyester and elastane), so it is possible that this variation of material fibers with the

Rib knit gave as a result a high wicking velocity, but more investigation on this special condition must be conducted to be able to determine that. Dryline Rib knit is a fabric designed to wick the sweat from the skin surface to an outer layer to evaporate it, apparently, as its wicking velocity presented here is good enough, its double layer mechanism designed for wicking also works to wick moisture in an upward way. Liverpool knit features a texturized side and apparently this condition slows down the wicking drastically. Fabric No. 36 features a 2x1 Rib knit but its velocity is below the average close to the French Terry fabric. This last one, as the interlocked, is knitted by having two layers but each one looks different. Purl knit performs with a good velocity above the average.

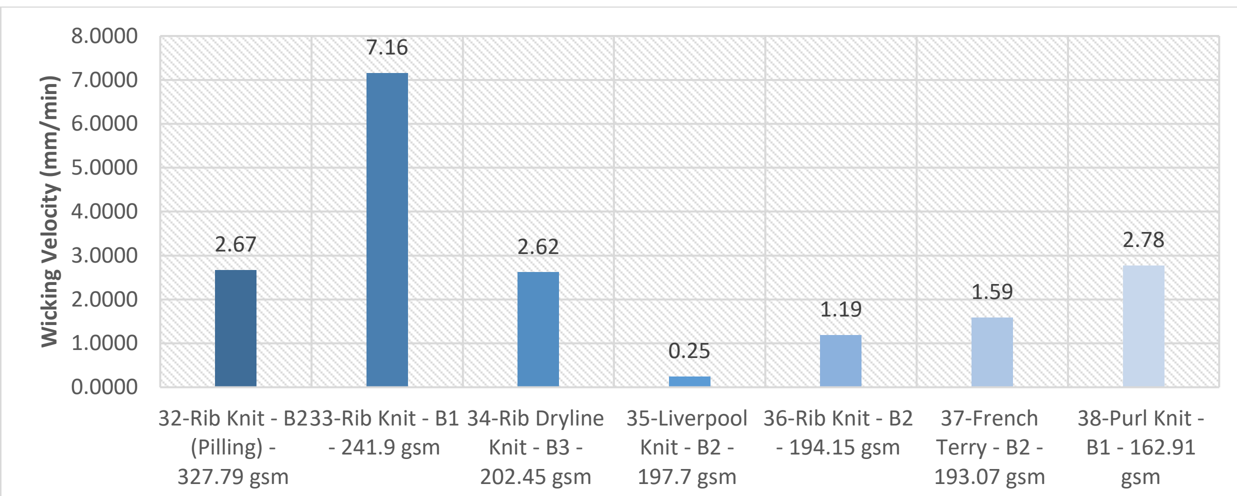

Figure 47: Wicking Velocity for Mixture Knitted Fabrics.

2.5.5 Findings

Simple woven 100% Cotton fabrics are expected to perform with a good wicking velocity in the average range. However, some conditions can negatively affect the wicking, that is the case of having dyed yarns or printed fabrics, the paint used by manufacturer seems to interfere with the wicking process, therefore when selecting a fabric, those conditions must be avoided.

Crinkle structure has been found to worsen the wicking. Pilling improves the wicking velocity. Utilizing a Canvas or a Twill woven pattern cannot be considered as a way of improving the performance. 100% polyester simple woven features a slower wicking velocity than the 100% cotton version, and the mixture versions are closer to the cotton one. However, basketweave 100% Polyester fabric has been found to have very good velocity. And Chiffon and Seersucker are the contrary case with very slow velocities.

Simple Jersey knit is better at wicking than simple woven, both are the most commercially available fabrics. Double layer knit fabrics showed a worse wicking velocity. Knit fabrics with high SVD like the Waffle Terry and the Pique knit displayed one of the highest wicking velocities observed, its high variability in structure is believed to be the responsible factor. Fleece knit have a generous amount of pilling on its surface and performs above the average velocity, so pilling does not improve wicking as a high SVD does. Interlocked fabric has an above average velocity even that it has a double layer arrangement, its polyester version featured a slower wicking. Constantly, polyester Pique knit overpass the cotton version. Travel knit has been identified as not good for wicking. The texturized face of the Liverpool fabric caused a very slow wicking. Rib knit 2x1 and French Terry have a velocity below the average. In the other hand, Purl knit is above the average. Dryline Rib knit used in sports clothes to wick sweet does a good job wicking moisture here. Two Rib knits 1x1 displayed a huge difference in wicking velocity, the slower one features a good amount of pilling, so apparently this is not sufficient to reach the velocity of the second Rib knit fabric. The particularity of Fabric No. 33 is its Heather Grey color/composition, to get the look of a disordered shades of grey, this fabric is created by mixing several fibers to make the yarns (Heather Fabric | Types of Cotton Fabrics, n.d.). This mixing could be the reason for such high wicking velocity of 7.15 mm/min.

2.6 Performance Comparison Between Water Retention and Wicking Analysis

A combined analysis on the performances of water retention and wicking can provide information on how in the parameter could benefit one performance and detriment the other, benefit both, or detriment both. Figure 48 allow us to see the performance of some fabrics in Water Retention Measure and Wicking velocity at the same time. Fabric 08 have a high water retention and a low wicking velocity, Fabric 09 also is slow at wicking, and as previously identified both have dyed yarns, so that can be the reason for the slow wicking but the WRM does not seems to be affected. Fabrics No. 10 and No. 11 both have similar wicking velocity but different WRM, the one with the higher WRM is because its pilling on the surface. Meaning that in this case the pilling didn't improve the velocity of No. 11.

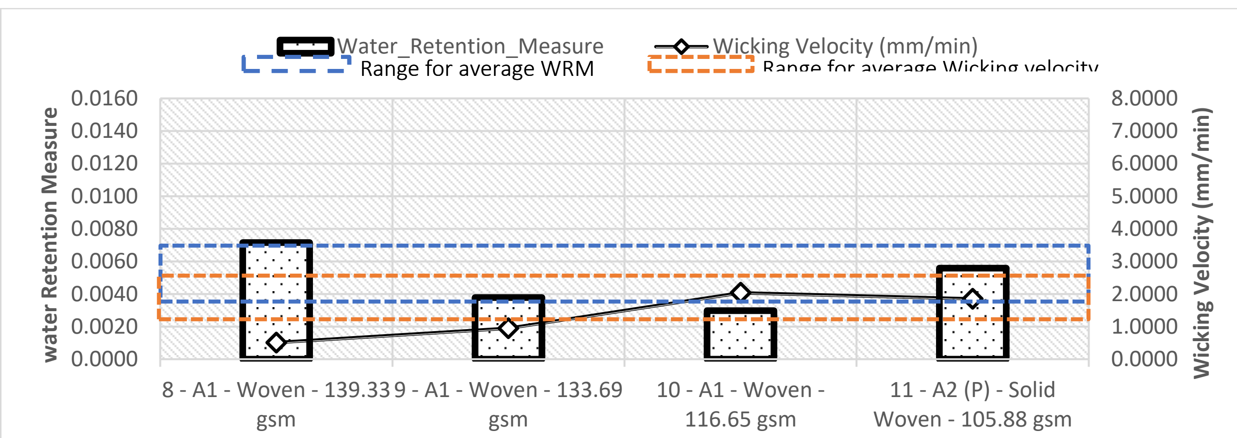

Figure 48: Water Retention - Wicking comparison for Lightweight 100% Cotton Woven Fabrics.

In Figure 49, Fabric No. 4 have the highest water retention and wicking but still on average values, that performance can be attributed to the large amount of pilling on its surface. Fabric No. 5 have an average WRM but low velocity, this is because its printed fabric, so it can be said that it affects only the wicking. Crinkle structure of fabric No. 6 seems to make performance below the average. Typical simple woven fabric No. 7 have an average performance on both aspects, so its simplicity can be characterized to a decent performance.

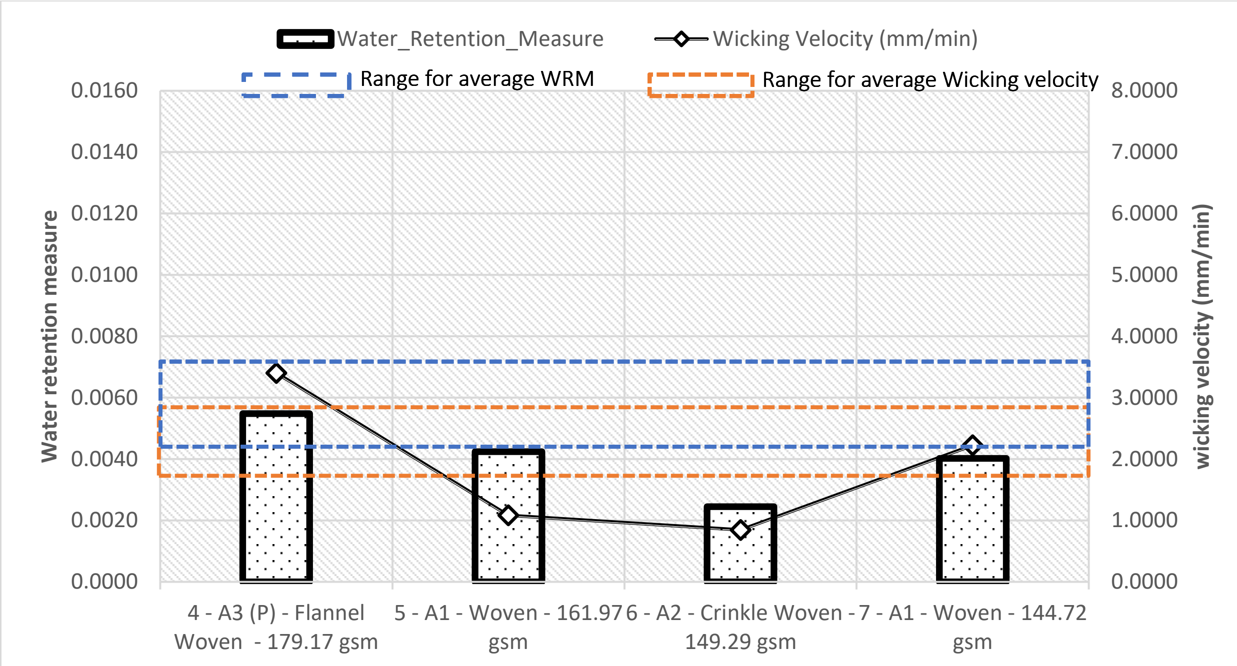

Figure 49: Water Retention - Wicking comparison for Mediumweight 100% Cotton Woven Fabrics.

Heavy fabrics of Figure 50 have all a below average WRM but a good wicking velocity, it is possible that their denser condition in combination of their woven patterns make them to be inefficient in terms of water retention. Fabrics performing poorly on one aspect but good in the other, cannot be considered as good performing cloth material overall. A good performance on both is what we are seeking to make the humidifier system as efficient as possible and produce the maximum freshwater possible.

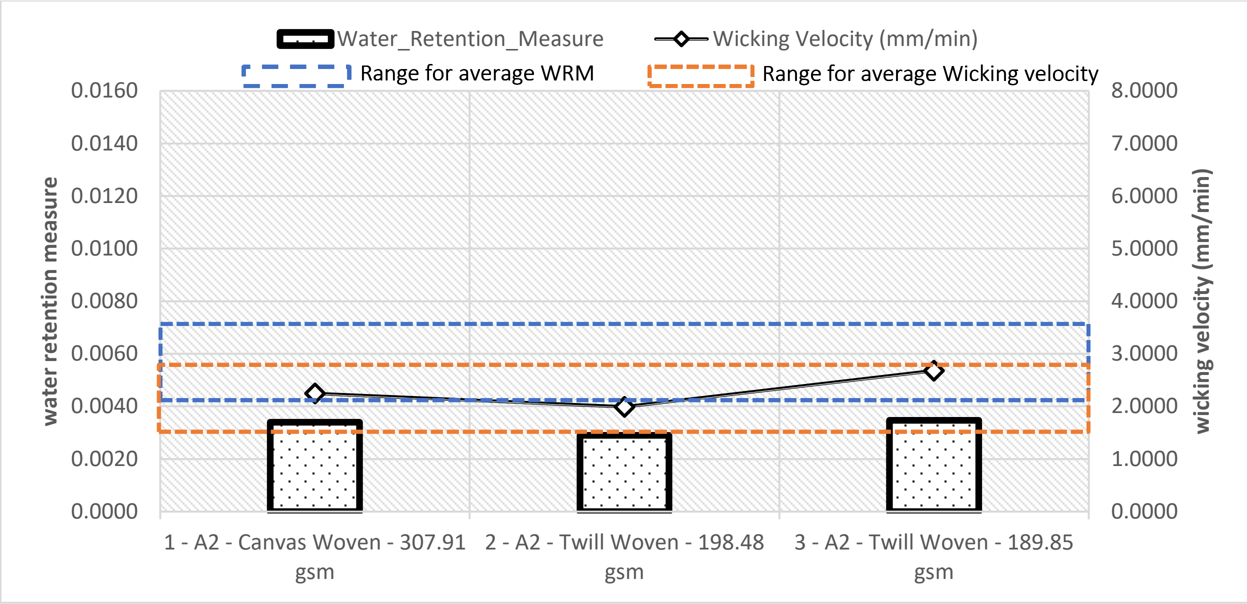

Figure 50: Water Retention - Wicking comparison for Heavyweight 100% Cotton Woven Fabrics.

100% Polyester woven fabrics from Figure 51 features different densities but all a low water retention performance and a very low wicking velocity except for fabric No. 12. Fabric No. 13 is very similar to No. 7, but its polyester condition can be the reason for the poorer wicking. In term of WRM, all the fabrics performs like the cotton woven, so apparently the material does not have a dominance over performance.

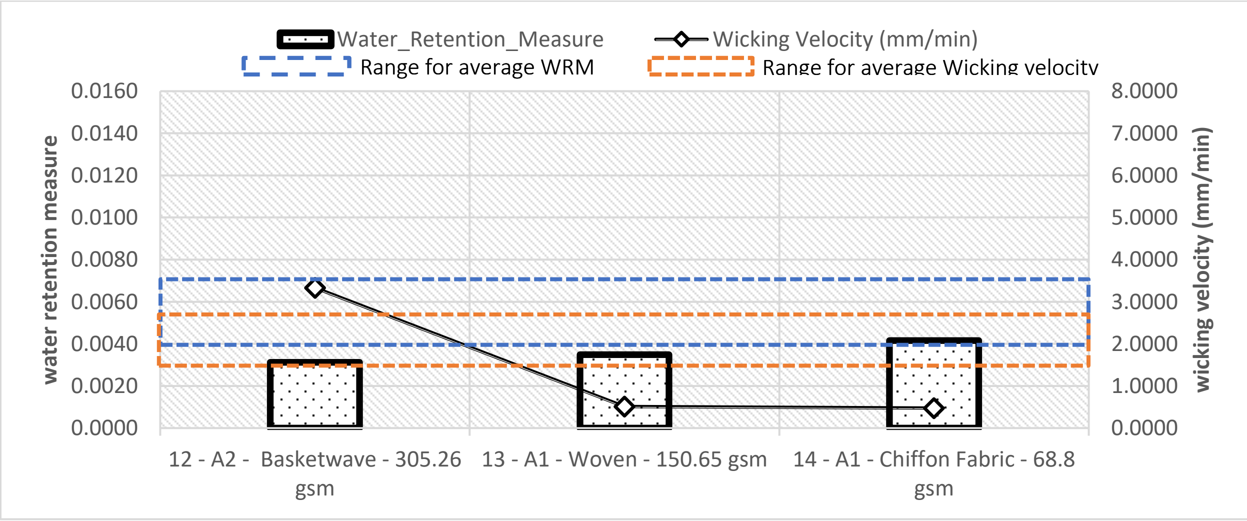

Figure 51: Water Retention - Wicking comparison for 100% Polyester Woven Fabrics.

Mixture woven fabrics of Figure 52 all present matching wicking velocities with the rest of the woven fabrics, but poorer water retention. Mixture material composition can be said to not change the wicking velocity when comparing with 100% polyester, but WRM is reduced significantly. Seersucker structure can be identified to benefit the water retention and worsen the wicking velocity.

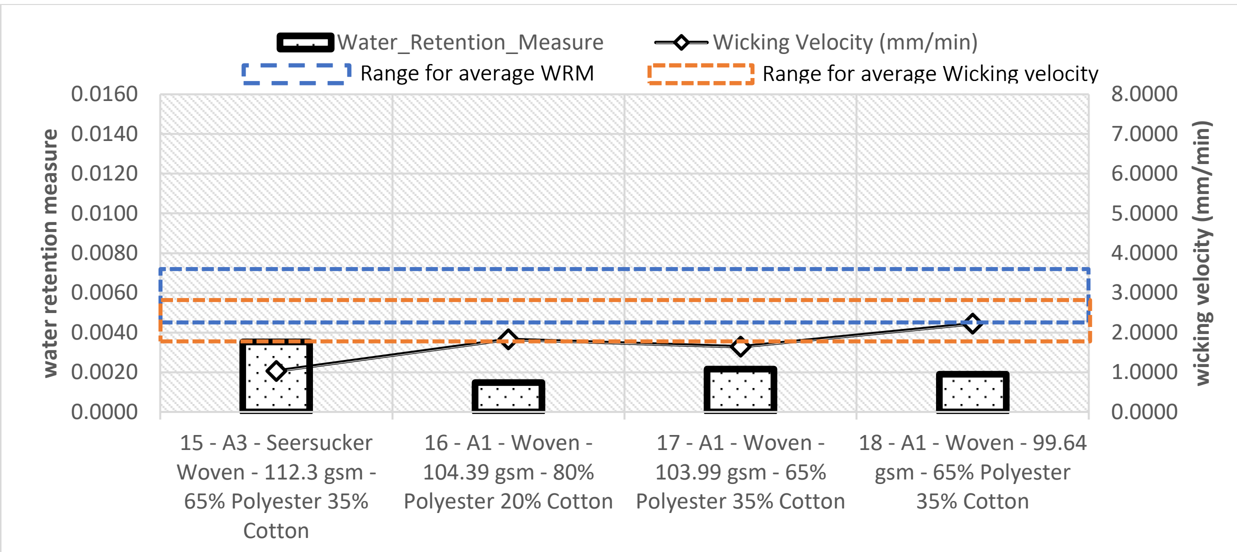

Figure 52: Water Retention - Wicking comparison for Mixtures Woven Fabrics.

Single Jersey knit presents a combination of good performances on WRM and Wicking velocity, better than most of the woven fabrics without pilling. When comparing to a double layer Jersey knit fabric in Figure 53, the water retention stays in the average range, but the wicking drops drastically. The cause of this can be the double layer structure.

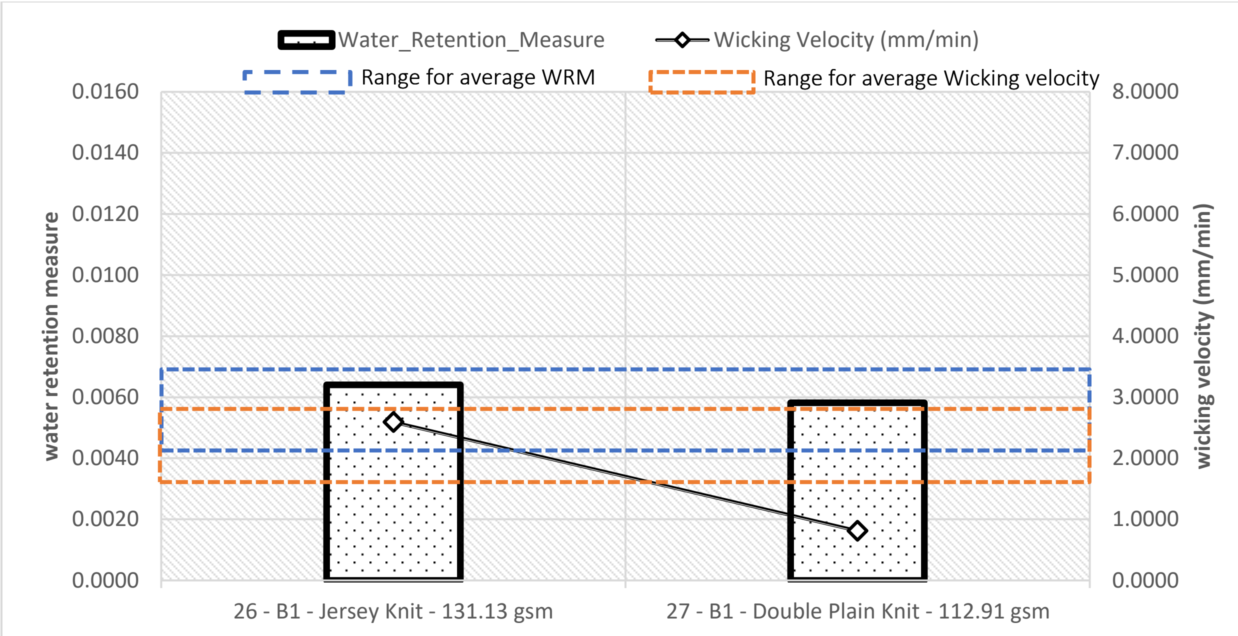

Figure 53: Water Retention - Wicking comparison for Lightweight 100% Cotton Knit Fabrics.

Similar case to the previous one is shown in Figure 54 where a Single knit fabric has similar WRM as a double layer fabric one but way higher velocity, again, this suggests the negative influence of having two-layer fabrics to the wicking but not to the water retention.

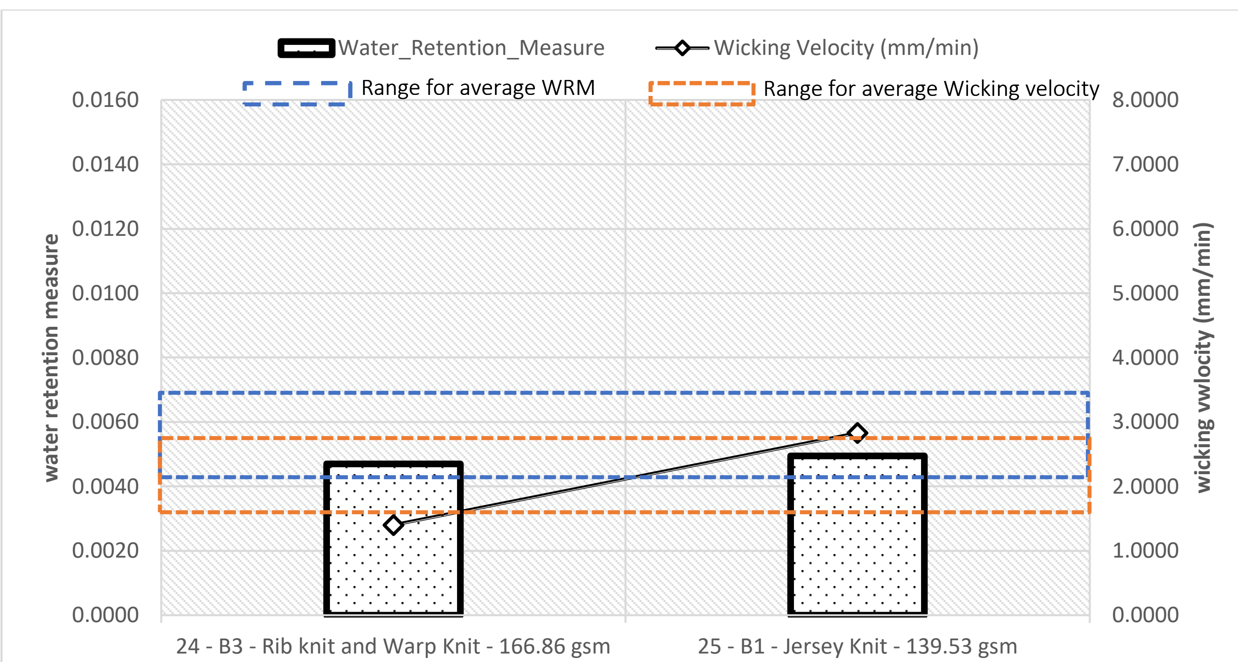

Figure 54: Water Retention - Wicking comparison for Mediumweight 100% Cotton Knit Fabrics.

Interesting finding can be obtained by analyzing the Figure 55. The high SVD fabrics No. 19 and No. 20 present contrasting performances by having high wicking velocity but low WRM. Waffle terry and Pique knit structure variation can be identified as the reason for such contrasting behavior. Fabrics No. 21 and No. 20 present some of the most balanced performances registered, both have a very high WRM and a wicking velocity near the upper average limit, so definitively, these fabrics can be considered as some of the best.

A balanced performance as high as possible is what is defined as good performance in this combined analysis. Fabric No. 23 is a very similar case as No. 24.

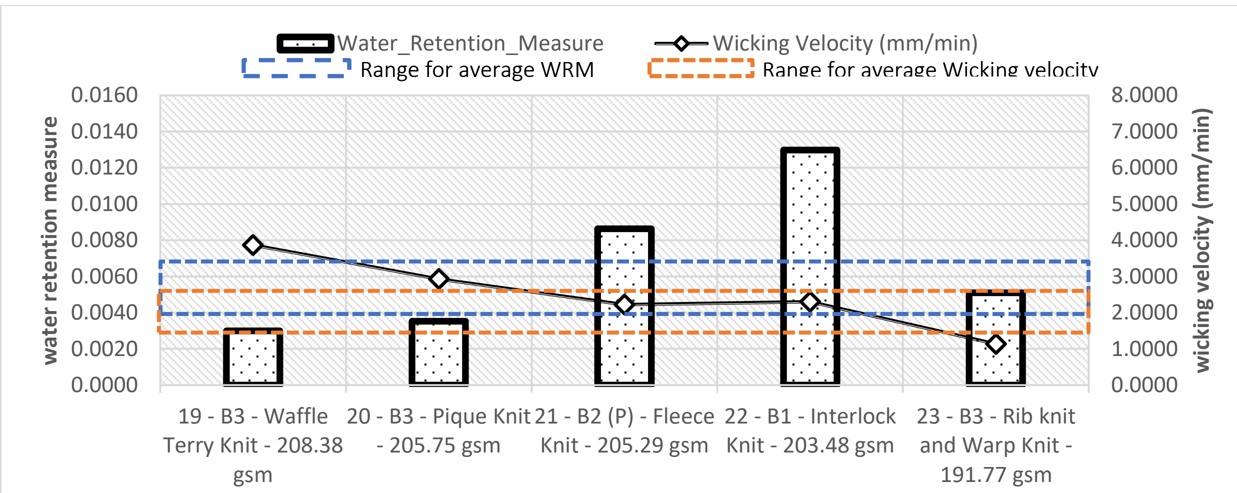

Figure 55: Water Retention - Wicking comparison for Heavyweight 100% Cotton Knit Fabrics.

100% polyester knitted fabrics of Figure 56 show a very high WRM for most of the fabrics, expect for high SVG fabric No. 29, and at the same time, it has the highest wicking velocity, while the rest are very slow. That can be because most of the fabrics of this groups are double layered, except for No. 30. So, the two-layer condition benefits WRM and worsen the wicking. High SVD B3 benefits the wicking and worsen the WRM (But it still on the average range). Travel knit is a peculiar case in which its combination of factor leads to have very high WRM and ultra-low wicking.

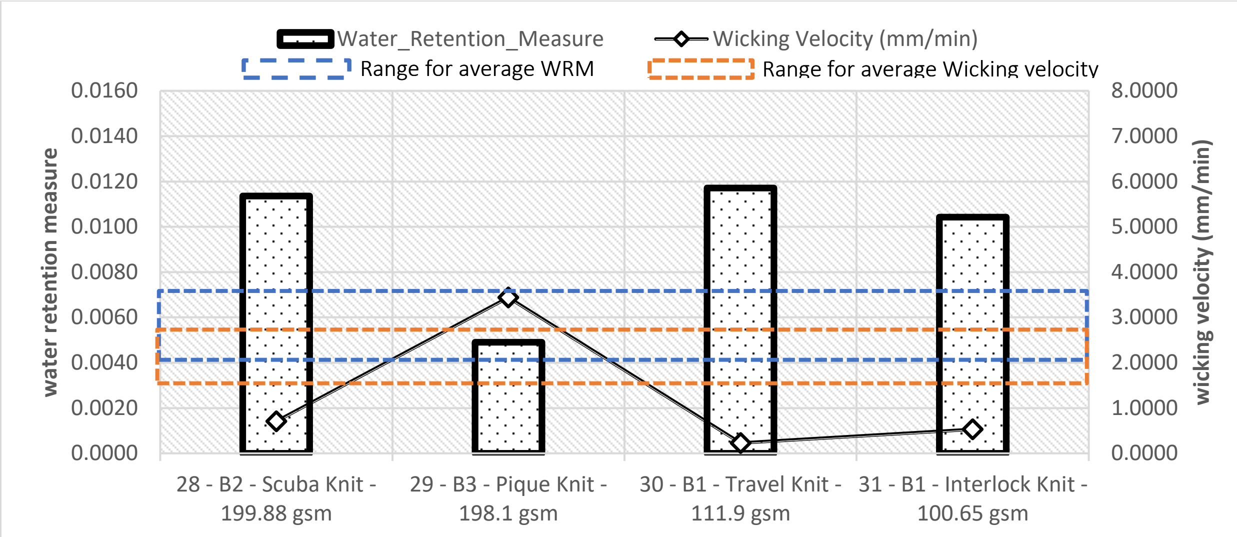

Figure 56: Water Retention - Wicking comparison for 100% Polyester Knit Fabrics.

Along with the heavyweight knitted cotton fabrics, some of mixture knitted fabrics of Figure 57 can be considered to be balanced. That is the case of fabrics No. 32, No. 33, and No. 34. All have a Rib knitting but different unique characteristics. Fabric No. 32 Pilling provides a balance on the average range values, fabric No. 33 with Heather composition have an average water retention but an ultra-high wicking velocity, and fabric No. 34 wicking designed structure performs a very high WRM, and an average wicking. Rib knit of fabric No. 36 does not have a particularity as the previous ones and performs near the low-average values. Fabric No. 35 have a texturized surface which can be pointed as the reason for its ultra-low wicking. No. 37 and No. 38 can be said that are balanced but at the low values of the average ranges.

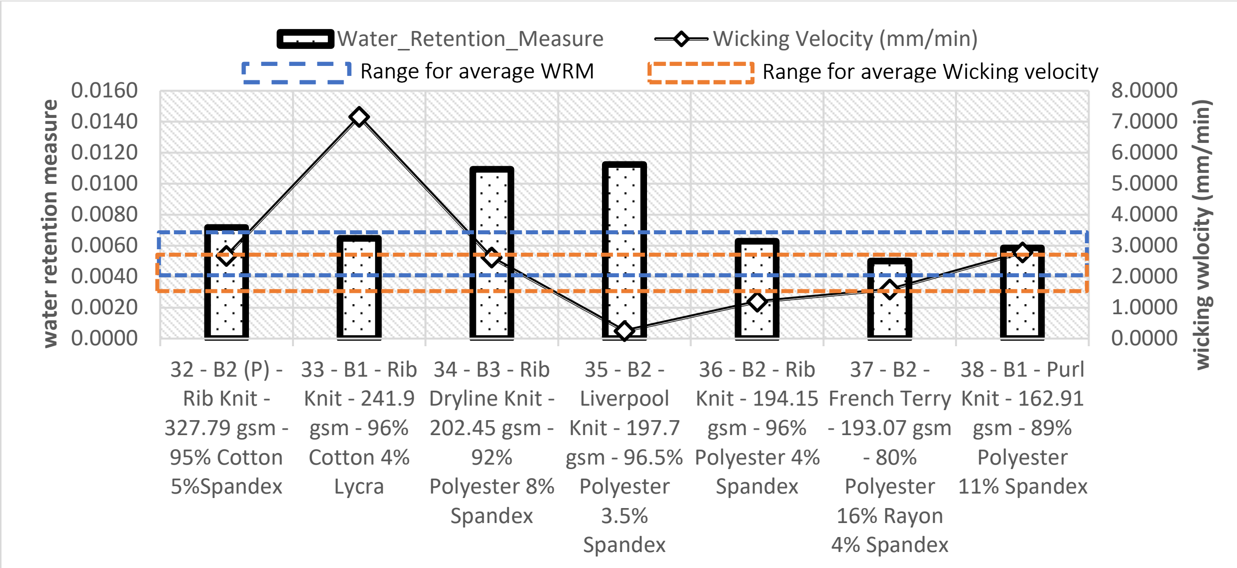

Figure 57: Water Retention - Wicking comparison for Mixture Knit Fabrics.

2.7 Fabric Selection

When selecting a fabric with a good water retention, density does not play an important role in determining the performance. The heavier and denser fabrics tested showed both Normalized Water Content and Water Retention Measure in the same range as the lighter fabrics, there is no point in selecting a fabric based only on its weight.

What can be identified as the most important parameter to consider when selecting a fabric is the weaving pattern. This is what the research has shown to be the dominant factor that can drastically change the performance. Results suggest that knitted fabrics with a consistent structure (low SVD) reached higher WRM values. Most of the better performers had a structure of double layers, so this condition might enhance the water retention. In a generalized definition, knitted patterns performed better than woven patterns, however, some woven and knitted showed an excellent performance due to pilling on its surface, so this is a condition to look for when selecting a fabric. Material composition of the fabric does have an influence on the performance, but it has been found that the weaving pattern is dominant over this parameter, in some cases 100% cotton version of a same fabrics performed better, while in other cases the 100% Polyester did. So, it cannot be determined a general definition of which material is better for water retention. In summary, it is convenient to look for a knitted fabric with a double layer structure that is closely weaved. If the fabric presents pilling, it is possible to have an enhanced water retention performance.

By selecting a fabric for the application proposed in this research, it is important to have a fabric material that can quickly wick the moisture to an air passage on the humidifier device. Typical regular plain woven does do a good job wicking water, but some conditions must be avoided: Crinkle structure, dyed yarns, and printed fabrics. Pilling is preferable to have because it can enhance the wicking velocity. 100% Cotton woven fabric is preferable over the polyester versions. Single Jersey does a better job in wicking than simple woven. Double layer fabrics showed a slower velocity than the single layer ones. However, some double layer as the Interlock still performs very well. The better wicking performers are the fabrics with a high SVD, the constant unevenness in the structure benefit the wicking. Texturized fabrics should be avoided due to their very low velocity. Heather grey color could improve the wicking due to how it is made combining different fibers to create yarns of different shades of gray, but further testing is needed to confirm this condition. In summary, a fabric with a changing knit structure it believed to show a quick wicking, it is preferable to be not a double layer material, and avoid dyed yarns, printed, or texturized fabric. Pilling can boost the performance as well as being Heather grey.

The criteria to select a fabric to use on the humidifier device can be complex. Mostly because some criteria to have a very good water retention negatively affects the wicking velocity. performance on one aspect sacrifices the performance of the other. So, a middle point must be found. For example, Liverpool fabric have an excellent water retention but the slower wicking velocity, this is an unbalanced fabric then. Rib Knit fabric No. 33 has the fastest wicking and the average water retention, and interlocked fabric has a very high water retention but an average wicking velocity, their performances does not math but at least are in or above the average range, so these fabrics can be considered as balanced. Testing should compare various cases to determine which one give the best performance. General recommendations suggest selecting a fabric with pilling, knitted pattern, heater grey color composition, and possibly made of cotton to ensure a quick wicking. Other parameters must be balanced in the trade-off of performance. This is by considering commercially available fabrics on the market.

The special characteristics identified through testing and analysis are summarized in Table 7 showing how they have been found to influence the Water Retention and the Wicking performance.

Table 7: Fabrics Add-on Characteristics and their influence for water retention and wicking.

Characteristics	Water Retention	Wicking
Pilling	Enhance	Enhance
Dyed Yarns	-	Worsen
Printed Fabric	-	Worsen
Texturized Fabric	-	Worsen
Double Layers	Enhance	Worsen
High SVG	-	Enhance
Low SVG	Enhance	-
Heather Grey Color/Composition	-	Enhance
Crinkle Structure	Worsen	Worsen

Evaluating the performance of the fabrics, average values were calculated for each test, normal distribution shows that the most common WRM values are in a range from 0.004 to 0.007, and most of the wicking velocities range from 1.50 mm/min to 2.75 mm/min, values outside those ranges can be considered as below the range, or above the average. Qualification of good or bad performance cannot be given so easily because it is highly relative to the application in which be applied. Therefore, in our application for HDH desalination, testing in the humidifier unit is needed to determine how good or bad it is a fabric depending on the performance of the whole system. Table 8 summarizes the performance of each of the weaving patterns based on how their values are positioned relative to the average ranges.

Table 8: Characterization of the weaving patterns performance.

Weaving Pattern	Water Retention	Wicking
Canvas Woven (A2)	Below Average	Average
Twill Woven (A2)	Below Average	Average
Flannel Woven (A3)	Above Average	Above Average
Crinkle Woven (A2)	Below Average	Below Average
Gauze Woven (A2)	Above Average	Average
Basketweave (A2)	Below Average	Above Average
Chiffon Woven (A1)	Below Average	Below Average
Seersucker Woven (A3)	Average	Below Average
Simple Woven (A1)	Below Average	Above Average
Waffle Terry (B3)	Average	Above Average
Pique Knit (B3)	Below Average	Above Average
Fleece knit (B2)	Above Average	Above Average
Interlock Knit (B1)	Above Average	Above Average
Double Layer (B3)	Average	Below Average

Table 8, cont.

Weaving Pattern	Water Retention	Wicking
Jersey Knit (B1)	Average	Above Average
Double Jersey Knit (B1)	Average	Below Average
Scuba knit (B2)	Above Average	Below Average
Travel Knit (B1)	Above Average	Below Average
Rib Knit (B1)	Average	Average
1x1 Rib Knit (B1)	Average	Best One
Dryline Rib Knit (B3)	Above Average	Above Average
Liverpool Knit (B2)	Above Average	Below Average
French Terry Knit (B2)	Average	Average
Purl Knit (B1)	Average	Average

Some fabrics can be highlighted by the testing results, Table 9 displays the weaving patterns that either have a performance on both Water Retention and Wicking velocity of average or above the average. A selection of some of the “Best” fabrics along with some of the “Worst” fabrics is going to be made to be tested on the humidifier to properly characterize the combined performance.

Table 9: Fabric selection for best performance on both water retention and wicking.

Fabric	Water Retention Measure	Wicking Velocity
Flannel Woven	0.0055	3.40
Gauze Woven	0.0056	1.85
Simple Woven	0.0040	2.22
Waffle Terry Knit	0.0030	3.86
Fleece Knit	0.0086	2.22
Jersey Knit	0.0049	2.83
Interlock Knit	0.0130	2.30
Rib Knit (1x1)	0.0065	7.15
Dryline Rib Knit	0.0108	2.61

CHAPTER III

HUMIDIFIER

One of three main components of a Humidification Dehumidification Desalination system is the Humidifier device, in this stage the seawater is separated into water vapor and salt and minerals residue. Since heating up the air enhances its water vapor carrying capabilities, a heat source acting on this device help the system to perform in a more efficient way. In the sea deployed HDH model, solar heaters will provide the necessary heat to complement the hot air source. The humidifier is designed to create zero high-salinity content brine, because its bottom part and the wave overtopping makes the water flow through a cycle, balancing the salt content naturally with the surrounding water.

3.1 Design

The unit has a top reservoir with a slotted base and a chamber below with a perforated bottom, and in between both, an array of vertical cloth sheets is placed. A photo of the test rig can be seen in Figure 58. The top reservoir is designed to contain water by means of overtopping, and by the leaking on the bottom of the top reservoir the water passes through the cloth sheets and runs into the below chamber creating a water film.

The array of fabrics has the purpose of enlarging the air-water contact surface, slow down the water overtopping flow and increment the air-water contact time. The pressure drop introduced by this array is low compared to other systems.

Figure 59 displays the structure of the device, the two reservoirs and the air passage can be clearly seen. Air enters the device by the inlet, pass through the array of cloth sheets by the air passage, and as the mini pump is providing water to the top reservoir, fabric will get wet and form a water film on its surface, so as the hot air enters and passes by, it will carry the moisture on the cloth sheets and deliver hot humid air at the outlet.

The slotted base of the top reservoir can be better appreciated in the top view of the device in Figure 60. Rectangular beams are placed in position with several shims to keep a gap of 0.0016 inches in between every beam to fit the fabric thickness, so flooding of top reservoir will occur at the same time as the water leaks through the fabrics, so eventually it reaches a balance, and the flooding remains constant at a certain level. This also ensures the sealing of the air passage; as water exists on the top and on the bottom, air leakage is eliminated, making all the flow to exit through the outlet and deliver the maximum possible flow of hot humid air.

Figure 58: Photo of the humidifier model.

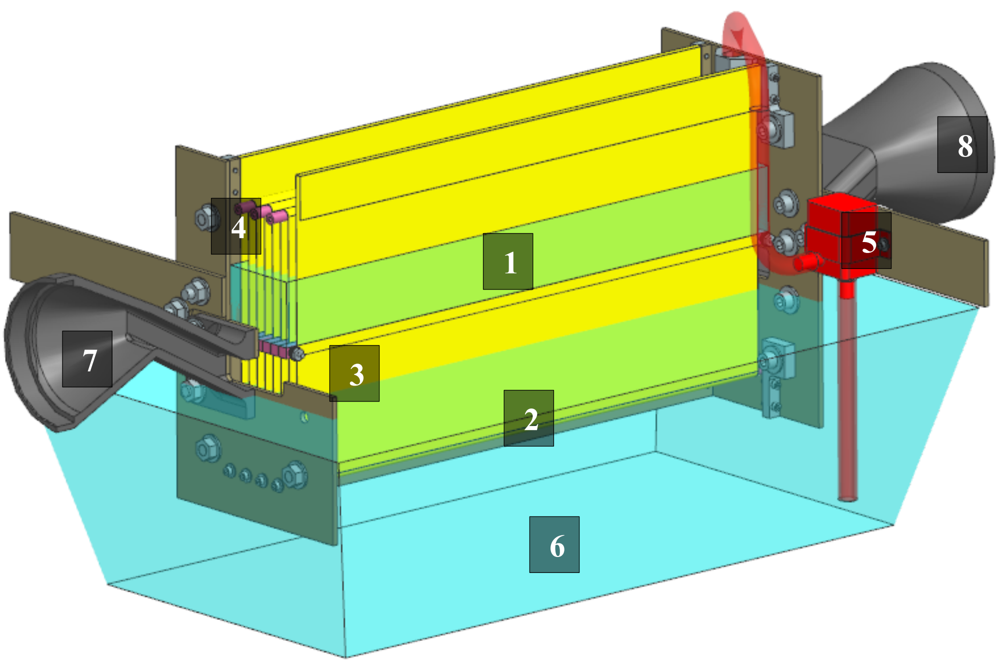

Figure 59: Open view of the humidifier device used for testing. 1) Upper reservoir filled with water by overtopping. 2) Bottom reservoir submerged in water. 3) Air passage. 4) Array of cloth sheets. 5)Mini pump simulating the overtopping. 6)Surrounding water. 7) Humidifier Inlet. 8) Humidifier Outlet.

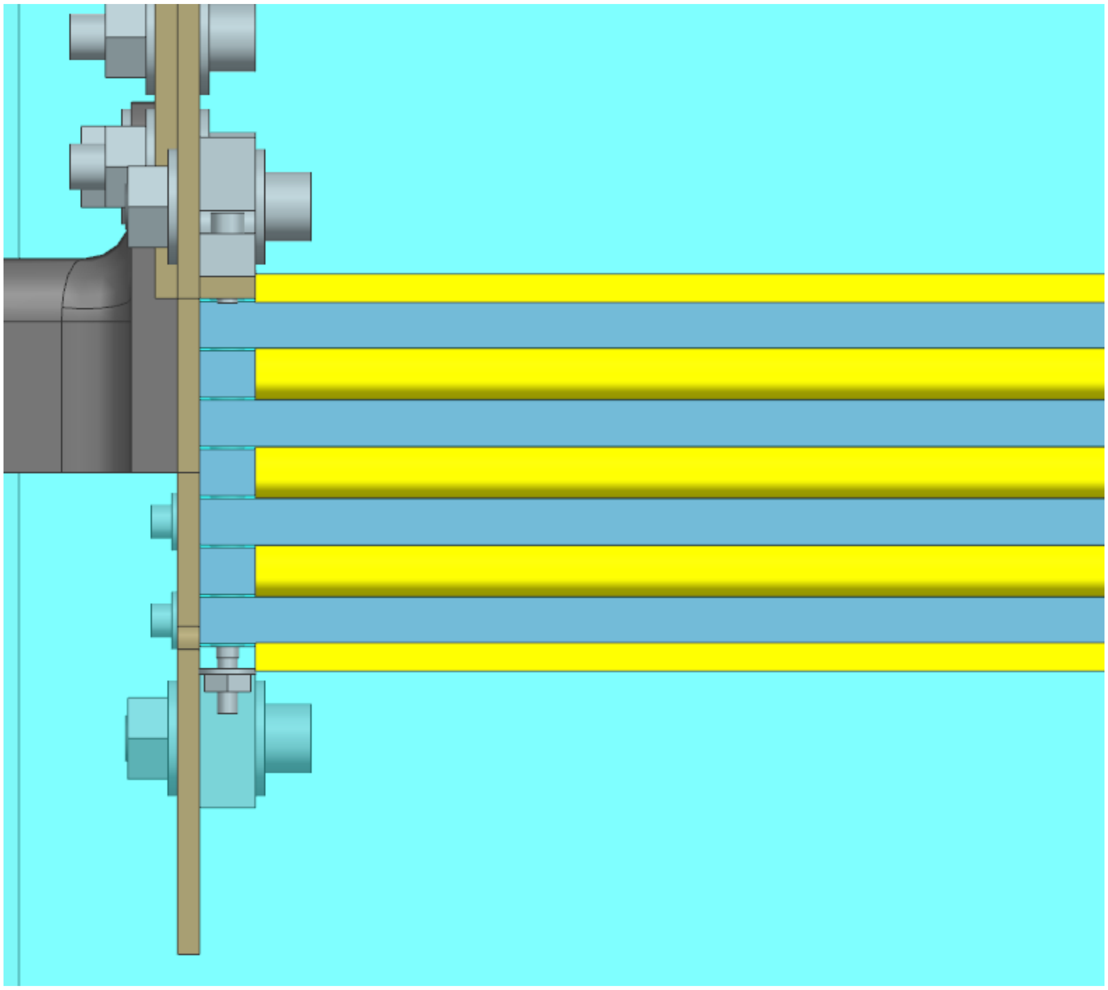

Figure 60: Top view of the humidifier showing the cloth sheets array going through the slotted base constructed by rectangular beams separated by 0.016in Shims.

3.2 Humidifier Testing

To test the influence of wicking performance and water retention of a group of fabrics, the system was run without the overtopping feature, therefore the wicking velocity plays an important role because this will be the only wetting mechanism. When comparing performance with different fabrics, the humidifier output should reflect the influence of the cloth material used. Water retention is also important, the performance can be influenced by the capacity of the fabric to have more moisture available to the air flow. If a fabric provides a good performance, it means that a hot fully saturated air is at the outlet at a stabilized temperature and relative humidity. But, if there is not a stable output or the air is not fully saturated, that means that the fabric is performing poorly. Testing with the water contained at different temperatures is considered to see how the fabric performance could change and how it affects the system. Measurement and analysis of the data obtained by testing can help to better understand the fabric influence and how the water retention and wicking performs together.

3.2.1 Setup

Testing setup is presented in the Figure 61. The hair dryer is sealed to a polycarbonate tube of 3 inches, so all the flow is conducted through the tube until it reaches the inlet of the humidifier. Several paper straws were put together to straighten the flow before entering he system. An intentional gap was left in between the connection of the polycarbonate tube and the inlet of the humidifier, this is because eliminating the gap leads to overheating on the hair dryer due to backflow, this gap also allows the control of the inlet flow rate. The humidifier has an acrylic cover to contain the evaporation inside, and a mercury thermometer is used to monitor the water temperature in the metal container. A double-burner provides the heat to the water used for humidification; continuous manipulation of the hot level is needed during testing to maintain the set point. At the outlet is where the temperature and relative humidity were monitored using an Omega OM-62 Data Logger and a SHT30 temperature and humidity sensor shown in Figure 62 connected to an Arduino circuit board linked to Excel Data Stream Add-on to monitor and record in real time the output of the system.

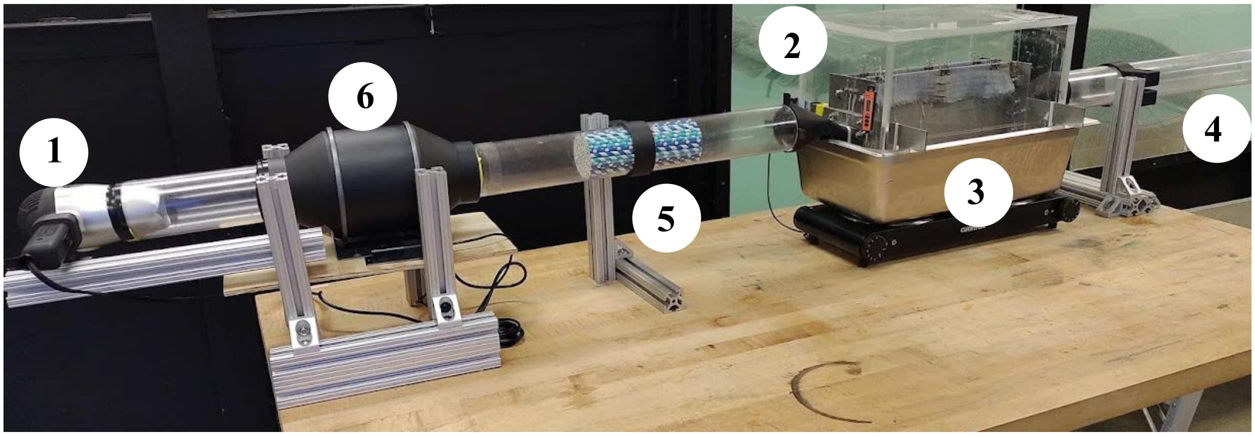

Figure 61: Humidifier testing setup. 1)Hair dryer. 2) Humidifier device with an acrylic cover. 3) Water container. 4) Humidifier outlet. 5) Flow straightener. 6) Flow booster device.


Figure 62: Humidifier Outlet with the OM-62 Logger and the SHT30 sensor placed to measure output air.

3.2.2 Parameters

Through preliminary testing, parameters were defined based on setting up a point in which the influence of the fabrics in the performance can be better appreciated. The hair dryer has three velocities in which the flow rate and temperature changes, velocity number 3 was selected because it provides hotter air at a higher flow rate, however, a gap of 1.25 inches was needed because the humidifier cannot handle very large flow rates. The temperature of the inlet air is around 100°C. Temperatures of the humidifier water are 60°C and 40°C for the two types of testing without water overtopping. The water level is set to have approximately 1 inch of fabric length submerged underwater. Usual testing time is 20 minutes, this was determined by evaluating the time required for each fabric to reach a steady state. All testing were performed in an air-conditioned laboratory at a temperature range of 20-24°C, and a relative humidity of 55 %RH ± 8%.

3.2.3 Fabrics Tested

The selection of the fabrics tested on the humidifier device has been made by considering the performance of each of the fabrics and the relationship between the water retention and the wicking velocity. Fabrics No. 07 and No. 25 were selected for their wide commercial availability and because both showed average performances. Fabric No. 13 was chosen because it is the polyester version of the simple woven, so we can observe if there exists some material influence.

Interlock and Rib knit fabrics are both balanced but have contrary performances, so testing both can possibly show interesting findings. Liverpool fabric is not balanced; has a very high water retention but ultra-slow wicking. This is a way to determine the importance of the wicking in no water overtopping mode. Table 10 summarizes the selection.

Table 10: Fabric selection for humidifier testing.

Fabric	Water Retention	Wicking	Balanced
07 – Simple Woven	Average	Average	Yes
13 – Polyester Woven	Below the Average	Below the Average	Yes
25 – Single Jersey	Average	Above the Average	Yes
22 – Interlock	Above the Average	Average	Yes
33 – Rib Knit	Average	Above the Average	Yes
35 - Liverpool	Above the Average	Below the Average	No

3.2.4 Results

Results from the humidifier testing are presented as a comparison of the output system stabilization behavior for each of the fabrics. Figure 63 shows the Relative humidity at the humidifier output for each of the fabrics during the testing time. This is for no water overtopping mode with water temperature of 60°C. It can be quickly appreciated that four of the fabrics have a similar rising curve and reach a stabilization point, but Simple knit or Single Jersey fabric along with the Liverpool fabric, have a sudden drop after certain time after staying in a saturation mode for a short period of time.

The temperature increases when the hot air is introduced, then the mixing of hot air with the moisture on the humidifiers happens, and the result of that mixing is reflected in the outlet. At the beginning of the testing, it takes some time to the system to reach a stabilization point in which the output temperature and relative humidity will no longer change. The stabilization is reached when a balance between the moisture content carried away by the air flow and the moisture introduced to the fabrics by only wicking is reached. Therefore, depending on the wicking capability of each fabric, the general performance of the humidifier will change.

In Figure 64 the temperature rise recorded for each of the fabrics are compared. Rib knit, Woven, Polyester Woven, and Interlocked fabrics reach a steady value after approximately 200 seconds, but Single Jersey and Liverpool fabrics temperatures continue to increase. The point in which those temperatures start to deviate from the rest correspond to the time when the relative humidity drop occurred.

The relative humidity drop behavior can be explained by remembering that for a steady state to occur, a balance between the wicking and moisture carried by air flow must exist, so the drop suggests that balance never happened, and when temperature rises, the moisture carrying capacity also rises, therefore those fabrics did not had the ability to maintain the introduction of moisture by wicking as the air gets hotter, so the air flow overcomes the wicking and the air continues to rise in temperature while the relative humidity drops, delivering at the exit a not saturated hot air.

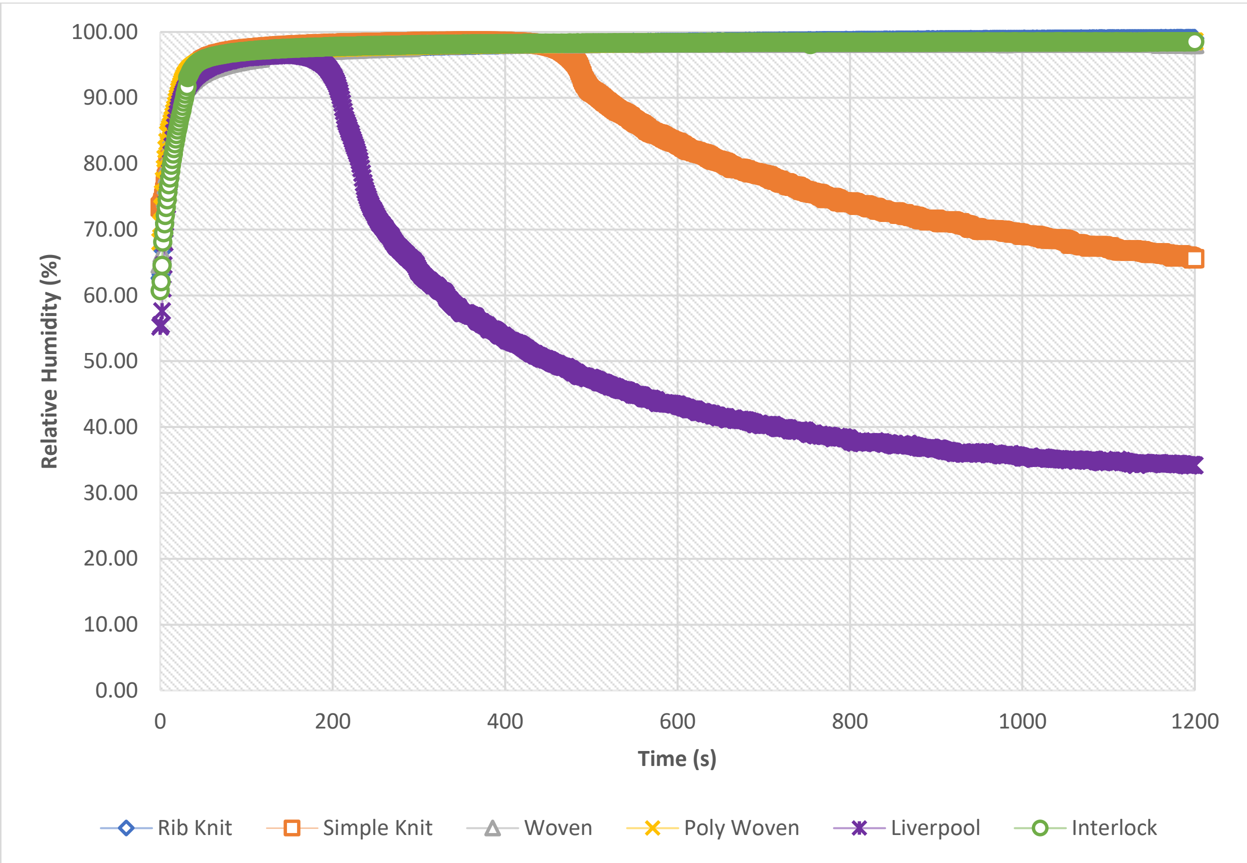

Figure 63: Relative Humidity (%RH) Plot for each Fabric tested.

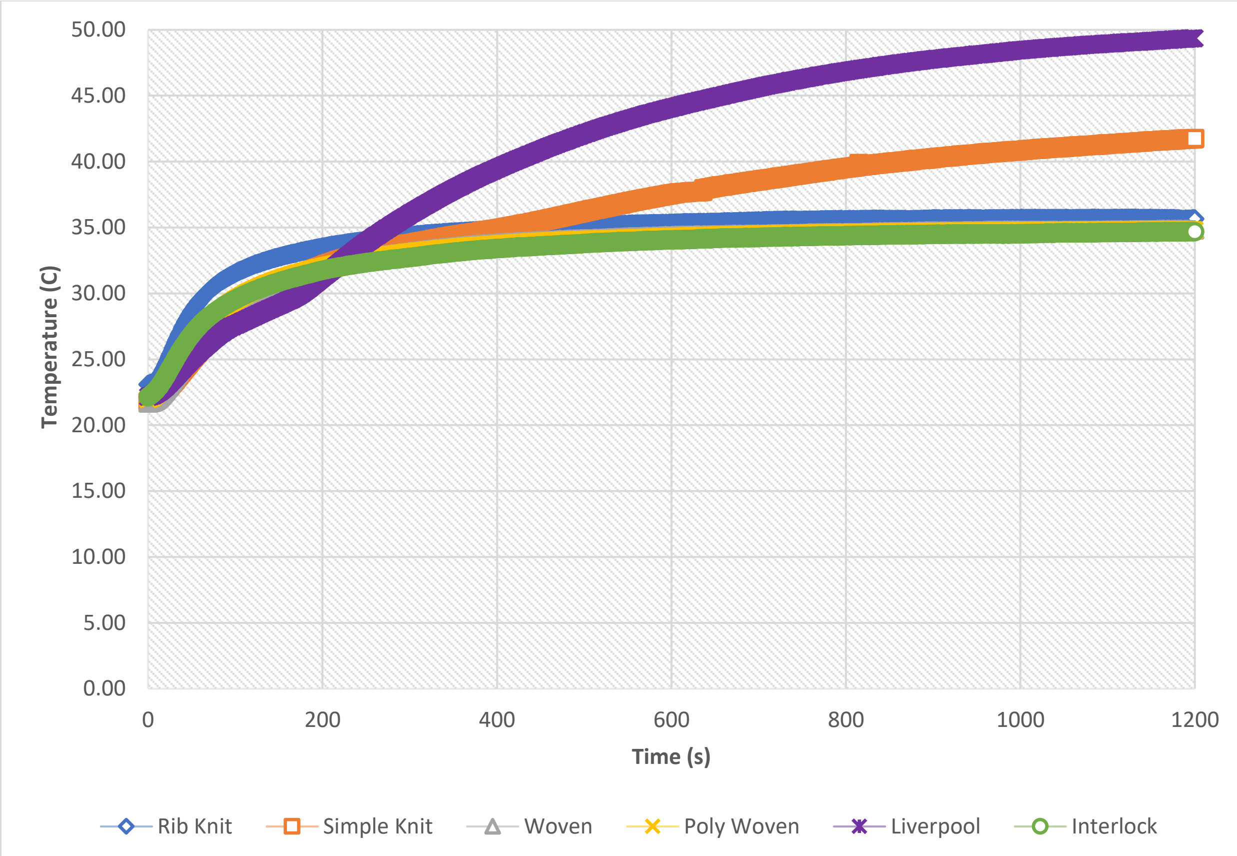

Figure 64: Temperature (C) Plot for each Fabric tested.

The results from the three testing are presented in the following tables. Water production was calculated by measuring the output air flow speed with a pitot tube, and based on the area of the outlet duct, the mass flow rate was calculated. Relative Humidity and Temperature values were taken from the steady state for each of the fabrics, so mixing ratio was calculated using an online calculator (PST | Michell Humidity Calculator, n.d.). Water production is measured in litters per day. An ideal condensation by a dehumidifier was assumed for calculations. Table 11 displays the water production without water overtopping at a water temperature of 60°C, and on Table 12 the production of freshwater presented is under the settings of no overtopping at a water temperature of 40°C.

Table 11: Water Production Results for Humidifier without Overtopping at a temperature 60°C.

No Overtopping, Water Temperature at the Humidifier: 60°C								
Fabric	Average Temperature (°C)	RH%	Mixing Ratio (kg/kg)	Ambient Mixing Ratio (kg/kg)	Difference Mixing Ratio (kg/kg)	Average Outlet Speed (m/s)	Mass Flow Rate (m3/s)	Water Production L/D
Single Jersey	41.76	65.59	0.03445	0.00726	0.02718	1.2	0.00547	12.9
Interlock	34.67	98.51	0.03532	0.00726	0.02806	1.2	0.00547	13.3
Rib Knit	35.65	98.99	0.03760	0.00726	0.03033	1.2	0.00547	14.3
Woven	34.82	98.12	0.03548	0.00726	0.02822	1.2	0.00547	13.3
Polyester Woven	34.79	98.56	0.03559	0.00726	0.02833	1.2	0.00547	13.4
Liverpool	49.36	34.20	0.02618	0.00726	0.01891	1.2	0.00547	8.9

Table 12: Water Production Results for Humidifier without Overtopping at a temperature 40°C.

No Overtopping, Water Temperature at the Humidifier: 40°C								
Fabric	Average Temperature (°C)	RH%	Mixing Ratio (kg/kg)	Ambient Mixing Ratio (kg/kg)	Difference Mixing Ratio (kg/kg)	Average Outlet Speed (m/s)	Mass Flow Rate (m3/s)	Water Production L/D
Single Jersey	38.23	60.94	0.02618	0.00726	0.01892	1.2	0.00547	8.9
Interlock	33.68	96.43	0.03259	0.00726	0.02532	1.2	0.00547	12.0
Rib Knit	32.80	98.52	0.03165	0.00726	0.02438	1.2	0.00547	11.5
Woven	33.47	97.85	0.03269	0.00726	0.02542	1.2	0.00547	12.0
Polyester Woven	31.81	97.87	0.02964	0.00726	0.02237	1.2	0.00547	10.6
Liverpool	46.43	24.88	0.01618	0.00726	0.00891	1.2	0.00547	4.2

3.2.5 Discussion

Analyzing the Figure 65 it can be observed that having the humidifier water at a temperature of 60°C the device will produce more freshwater than having the temperature at 40°C. Analyzing the scenario at a water temperature of 60°C shows that Interlocked, Simple Woven, and Polyester Woven fabrics produced nearly the same quantity of water, their outlet temperature in testing is near 34.5°C and 98 RH%.

Wicking velocities of simple woven and interlock fabrics are very close, and the WRM of Cotton woven and polyester woven fabrics are very similar. As the interlock fabric has a very high WRM and it performed similar to fabrics with an average WRM, it suggests that the water retention capacity is not as important as the wicking velocity in this setting. However, as polyester woven fabric also performed similar having a low wicking velocity of 0.5 mm/min, it will be complex to determine a minimum velocity value to maintain a steady state on the humidifier. The wicking velocity changing with the water temperature may be considered for future research. single jersey fabric had a drop of relative humidity on every test, so it is expected to produce less water. The performance drop was not predicted considering that it has a higher value of WRM and higher wicking velocity than the simple woven, the cause can be explained by introducing a variable that was not considered before: the stretchability and deformation of the fabrics. Among the tested materials, this was the one with more permanent deformation by stretchability, and this deformation can occur by wearing but mainly must be due to the process of placing the fabric in the humidifier device. The humidifier design requires the cloth to not be loose, so some tension had to be applied during the setting up, leading to eventually narrowing the cloth length and reducing the air-water contact are, and the thickness is reduced. As the knitting structure allows the deformation, the free space within the loops increments, augmenting then the material porosity. Woven clothes present almost no deformation. Knit fabric deformation may depend on each specific pattern. In absolute terms, single jersey fabric water production is below woven fabric by less than a liter per. Liverpool fabric have a high WRM but an ultra-slow wicking, such condition is reflected on the results; the relative humidity drop happens at the first 200 seconds. Rib knit fabric No. 33 performed the best on water production by approximately 1 more litter in a day that the Interlock fabric. Its good performance can be attributed to their high wicking velocity and an average WRM. Therefore, it can be concluded that wicking is of high importance in the no water overtopping mode regardless of the water retention capacity.

The humidifier is not designed to consider different thickness of fabrics. As highlighted in Figure 60 a shim of 0.0016 inches creates the gaps for the slotted base. This gap is designed for the Woven fabric No. 07. The polyester woven fabric closely matches the same density, but Single Jersey fabric is less dense, creating more free space in the fabric slots. In the case of thicker fabrics, the rods will compress the fabric incrementing the gap where the shims are located. In both cases, water leakage may occur from the top reservoir when the water overtopping is simulating the ocean waves. Interlock, rib knit, and Liverpool fabrics are thicker than the fabric that the gap was designed for. Future re-designs of the device should consider using an adjustable gap for different thicknesses. So, then the future testing can be performed under even conditions.

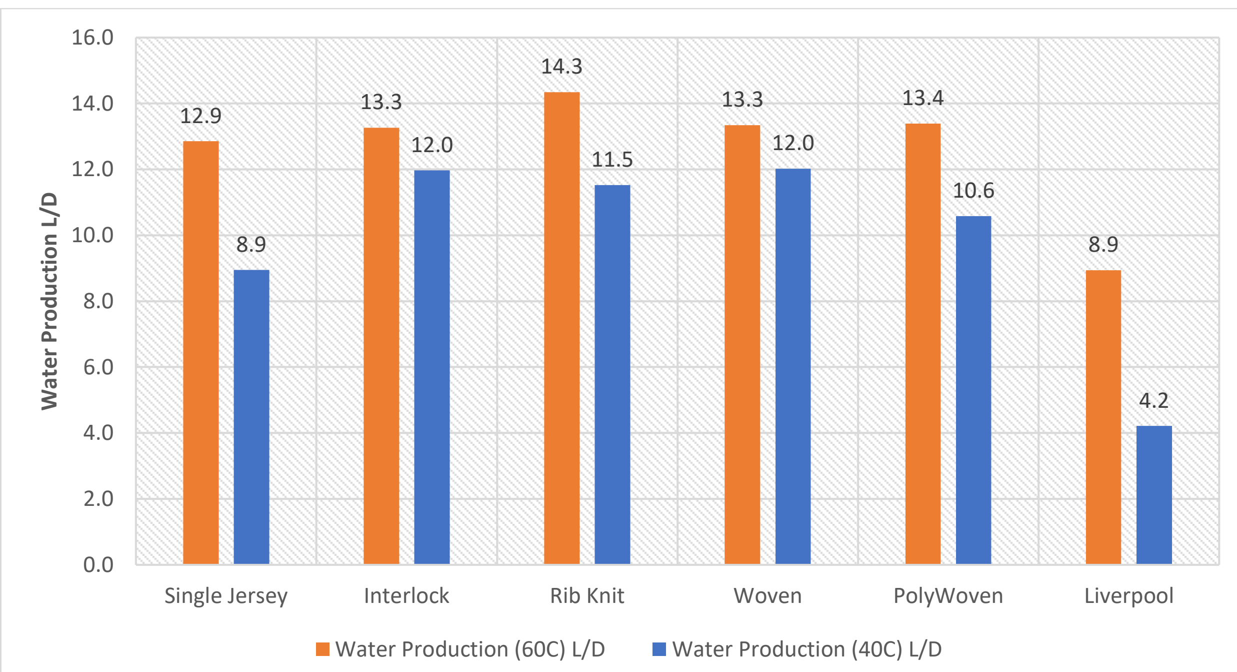

Figure 65: Comparison of Water Production for Humidifier without Water Overtopping at a temperatures of 60°C vs 40°C.

CHAPTER IV

CONCLUSIONS

A general summary of the conclusions obtained in this research are presented in this chapter. The fabrics section presents the knowledge acquired related to the fabric performance on water retention and what characteristics influence both water holding capacity, and capillary wicking. The humidifier section summarizes the testing findings of the different fabric performance to humidify air. Recommended future work to expand on the findings of this study are also discussed.

4.1 Humidifier Fabrics

Study of the water retention capacity and wicking velocity for each of the fabrics allowed the characterization and identification of the parameters than affect positively or negatively both characteristics. All 38 fabrics tested were selected by the common availability on the market and the contrasting differences between them. A balance between water retention and wicking velocity must exist to classify a fabric as a good performer. If one of the two performances is poor, that fabric may not be suitable for the discussed application of humidifying air since it minimizes the amount of water that will be in contact with the passing air. Results analysis by groups under similar conditions shows that the density is not dominant for the fabric performance. Rather, the dominant factor is the weaving pattern. It is important to highlight that some patterns can be simple and constant while others can be complex and variable. For that reason, the structure variation degree (SVD) was defined and assigned to every fabric tested by evaluating their structure. Fabric add-ons can either benefit or worsen the performance, the following findings were identified: Water retention can be enhanced by pilling, by a double layer structure, and by a low SVD. And it was observed that it decreases by a crinkle structure. Wicking can be enhanced by pilling, high SVD, and heather color structure composition, and worsen by dyed yarns, printed fabrics, texturized fabrics, double layers, and crinkle structure. In general, knitted fabric showed higher wicking velocities and water retention capacity than the woven fabrics. Exceptions exist, especially due to the fabrics add-on characteristics. High SVD can benefit the wicking because it gives a changing porosity by having different air spaces, and that can augment the wicking force, but also increment the air-yarns contact, incrementing the evaporation and thus reducing the water retention. However, results shows that such negative impact is not as big as the benefit to the wicking. On the other hand, low SVD in combination with a two-layer structure benefits the water retention by having more material weaved together with more intern yarns being less exposed to the ambient and thus reducing evaporation. These two conditions have been also identified as negative for wicking by reducing the velocity drastically in some cases. These contrasting performances correspond to an unbalanced fabric, which is not desired for this research, rather, a balanced performance is desirable by having above average performance for both water retention and wicking.

Material influence cannot be defined by generalizing, it will depend on weaving pattern. Testing shows mixed results for material influence, in wicking pure cotton fabrics performed better than pure polyester, but knitted fabrics made of mixtures presented high velocities. Water retention did not show a clear tendency. For those reasons it is said that weaving pattern (with structure variation and fabric add-on characteristics) is dominant to determine the performance, then the material, and last the density. Weaving patterns identified showing a good balance between their performance in water retention and wicking are: Flannel Woven, Gauze Woven, Simple Woven, Waffle Terry Knit, Fleece Knit, Single Jersey Knit, Interlock Knit, Rib knit (1x1), Dryline Rib Knit.

4.2 Humidifying Results

Testing of a group of fabrics on the humidifier device has shown that the performance can be enhanced by the fabric influence. Since the HDH Desalination system is meant to be deployed in the ocean, two conditions exist: 1) the surrounding waves introduce water into a top reservoir of the humidifier by overtopping, hence, completely saturating the fabrics. And 2) on calm days, the wetting of the fabrics is only influenced by the capillary wicking from the bottom reservoir of the humidifier. Therefore, a group of fabrics with contrasting characteristics for water retention and wicking were selected to test on the humidifier device to replicate these two conditions in a laboratory setting.

Testing was performed at two temperatures for the water, 40°C and 60°C. Testing with the water temperature at 60°C resulted on a better air-water mixture than when the water was at 40°C for all fabric cases. This is because the capacity of air to hold water vapor increases as the temperature increases, therefore yielding on an increased water production. It has been identified that the wicking plays an important role in the air humidification when there is no water overtopping. A balance between the inlet air flow carrying away the moisture of the fabrics and the wicking introducing the moisture to the fabric must be reached in order to the system to operate in a steady state. At this point the outlet air has a constant flow with constant temperature and constant relative humidity. This balance is not reached in the case of the Liverpool and Single Jersey fabric; relative humidity drop happens quick in the testing, making the humidifier to exhaust hot non-saturated air. Liverpool fabric has an ultra-slow wicking and a very high water retention, and it fails maintaining a steady point due to their poor wicking velocity. Therefore, it can be concluded that wicking is a determinant parameter when there is no water overtopping on the fabrics. Single Jersey has a high stretchability and deformation that seems to decrease its performance to humidify the air. The rest of the fabrics were able to reach a steady relative humidity and temperature point after 200 seconds showing saturated air with over 95% RH at the outlet. Interlock Knit, Simple Woven, and Polyester Woven fabrics produced nearly the same humidity on the air resulting on very similar water production even when the polyester fabric have a slow wicking. This could suggest that fabric wicking velocity might change as temperature of water increases. Rib knit which has high wicking velocity, produced the best air-water mixing and higher water production than the rest, reinforcing again the role of the wicking on an increased performance of the fabric for humidification applications.

4.3 Future Work

Future investigation on the changes of water temperature for the water retention and wicking velocity should help better understand the performance of the testing of the humidifier under hot water conditions. However, to correctly test with different temperatures and avoid having a temperature gradient, isolation of the test site with an ambient air temperature near the water temperature may be needed. Humidifier unit re-design with an adjustable gap of the slotted base can help avoid water leakage from the top reservoir for all the fabric thickness cases. Fabric tightness adjustment mechanism can reduce the test variations on high stretchable fabrics because stretching could change the thickness as it is the case of Single Jersey fabric. Easy to change fabric design can reduce the setup time before each test on the humidifier. Research on a variated small group of fabrics with the knitted patterns identified to have a balance between water retention and wicking, and having the add-ons identified to benefit the performance, can expand the understanding of what makes a fabric enhance the water production.

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APPENDIX

APPENDIX

STATE OF THE ART DEVICES AND SOFTWARE USED

Table 13: State-of-the-Art Equipment.

Equipment	Purpose	Results Obtained
Humidifier Test Rig	Validate the proposed humidifying concept	The heat generation mechanism proposed has been proven to work. An increase of temperature at the unit heating chamber has been registered.
Omega OM62 Data Logger	Measure temperature and humidity	Temperature and humidity of the environment and of the humidifier outlet air registered.
Raspberry Pi 3B+ with Raspberry Camera	Manage and capture the testing videos.	Video capture at desired framerates for data acquisition
Arduino with SHT30 I2C Temperature and Relative Humidity Sensor.	Sense the Temperature and relative humidity of an air flow.	Temperature and Relative Humidity from the humidifier outlet captured.

Table 14: State-of-the-Art Software.

Equipment	Purpose	Results Obtained
Microsoft Excel	Sensor data collected	Data collected from humidity and temperature sensor processed and visualized
Siemens NX	Parts, structure, and assembly design.	Design and assembly of humidifier test unit and heat generator test unit
Python 3.10	Control the Raspberry hardware to capture testing data.	Script created to capture video.

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