Clothing Comfort: Its Assessment and the Role of Fibre Type

PREAMBLE:

Comfort not only affects a person's well-being but also his/her performance and efficiency. Nevertheless, the perception and experience of comfort are highly complex and subjective, comfort often being defined as 'the absence of discomfort'.

One of the main functions of clothing is to keep the wearer as comfortable as possible under the 'normal' or 'everyday range' of external conditions, and activities (e.g. office-wear, sports-wear, outdoor-wear etc.) which the wearer is due to experience during the wearing of the clothing, as well as to satisfy other requirements or needs, such as adornment, status, modesty, position, fashion etc. Important functions of 'protective' type clothing, on the other hand, could include protection against extreme and/or potentially harmful, even fatal, external stimuli or elements, such as heat, fire, cold, micro-organisms (various bacteria, fungi etc.). It can be rightfully said, that in many ways, clothing acts as a 'second skin', forming the interface and barrier between the human being and the environment, and that the choice of clothing is influenced by many subjective and objective factors. **Figure 1**, (Das and Alagirusamy, 20/0) captures some of the factors involved in the selection of suitable clothing, while Table 1 (Angelova, R.A.) lists textile and clothing factors determining human comfort.

Table .1: Factors Related to Textile and Clothing that Determine Human Comfort (Angelova, R.A.)

HUMAN COMFORT

	Physical	**Physiological**	**Psychological**
DEPENDS ON	**Touch**	**Thermal Perception**	**Texture**
	Sight	**Sense Perception**	**Colour**
	Smell	**Movement**	**Design**

The four important aspects of comfort related to clothing are: 1) Thermo-physiological Comfort, 2) Skin Sensorial Comfort, (e.g. scratchiness, itching), 3) Ergonomic Comfort and 4) Psychological Comfort (Micheels, 1998 →). Wear Comfort is stated to be (Dolez *et al*) a quantifiable consequence of the body-climate-clothing interaction. Regardless of the clothing usage, the fabrics are expected to provide comfort, functionality and protection to the wearer from normal to extreme conditions under which they are to be worn, and for which they were specifically designed and chosen. Fabric properties can essentially be divided into two groups, or categories, namely aesthetic and functional.

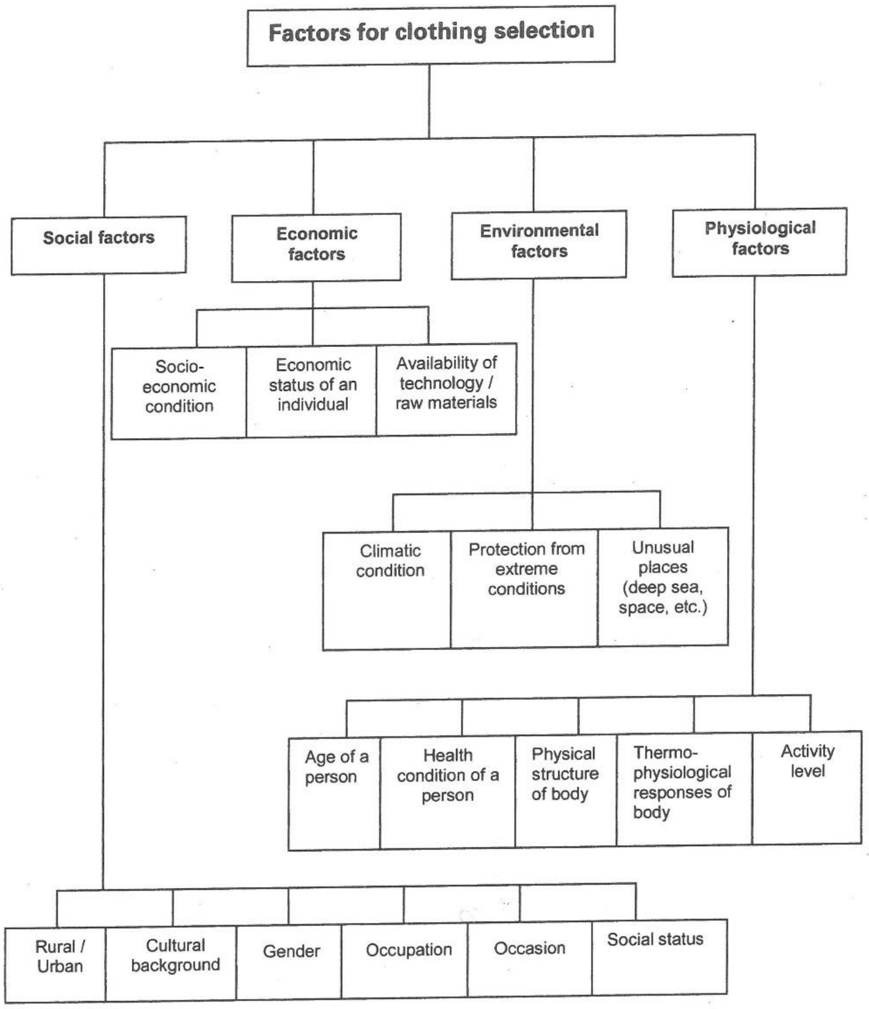


Fig. 1: Factors Affecting the Clothing Selection (Das and Alagirusamy)

With respect to what is probably clothing's most common and important role namely maintaining the wearer comfortable during every-day (non-extreme) activities and external conditions, and the assessment thereof, there have been conflicting results and findings published on the significance and role of fibre type (i.e. fibre 'substance' and morphological and chemical structure), notably natural *vis a vis* man-made fibres, in this respect. In particular, where-as wearer-trial results and findings almost without exception favour the natural fibre, for example wool, rather than the synthetic fibre, laboratory (i.e. instrument) assessment of comfort related properties, notably thermal insulation and water vapour transmission, mostly find little effect of fibre type *per se*. In view of this anomaly and since natural fibres, such as wool, are both widely regarded and accepted as being more comfortable than their synthetic counterparts, such as polyester, it was decide to review relevant scientific and technical literature in an attempt to clarify, and if possible, resolve the anomaly. The focus of this review is therefore, essentially on the results and findings of wearer trials *vis a vis* those of laboratory (instrument) assessment of clothing comfort, and more specifically the role of 'fibre type *per se*.

There is a vast literature, including textbooks, dealing with clothing comfort in its broadest context, most of which fall outside the scope of this review and which will therefore only be touched upon under the **Introduction**, with relevant references given for further reading.

INTRODUCTION:

Many factors play a role in the selection of clothing (**Fig. 2**, Li, 2001 Stoffberg), with comfort undoubtedly one of the key aspects of clothing, and in fact of human needs.

Fig. 2: Clothing Requirements of Consumers (Source: Li, 2001)

Nevertheless, it is extremely difficult to define comfort in all its diversity and ramifications, since it is not only extremely complex but is also largely subjective and personal, with an interaction between physical, physiological and psychological factors (**Fig. 3,** Li, 2001) and with the surrounding environment when wearing a garment (**Fig. 4**, G. Song 2011).

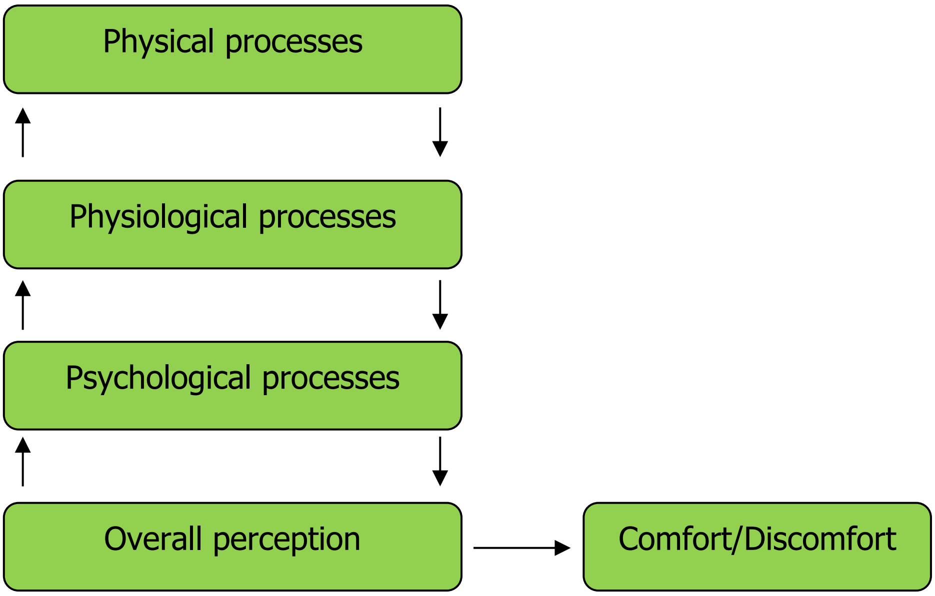


Fig. 3: Subjective Assessment of Overall Comfort (Source: Li, 2001)

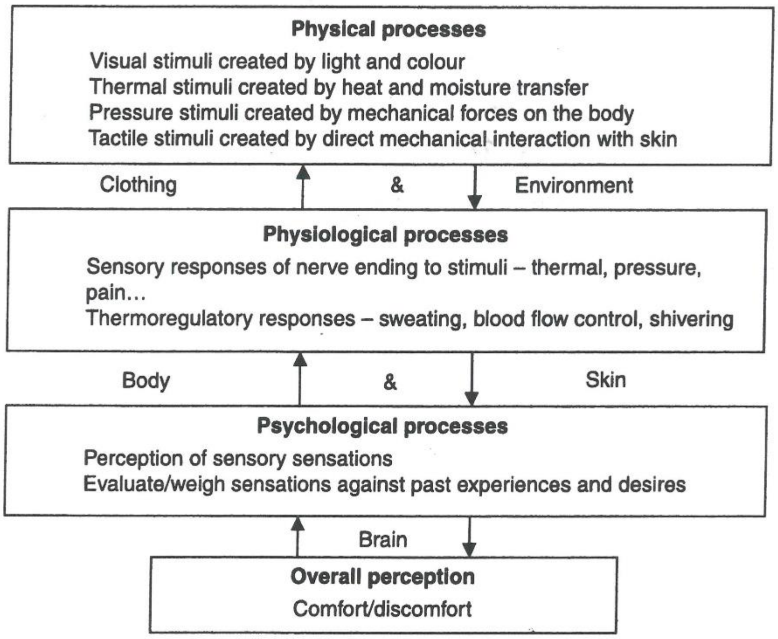


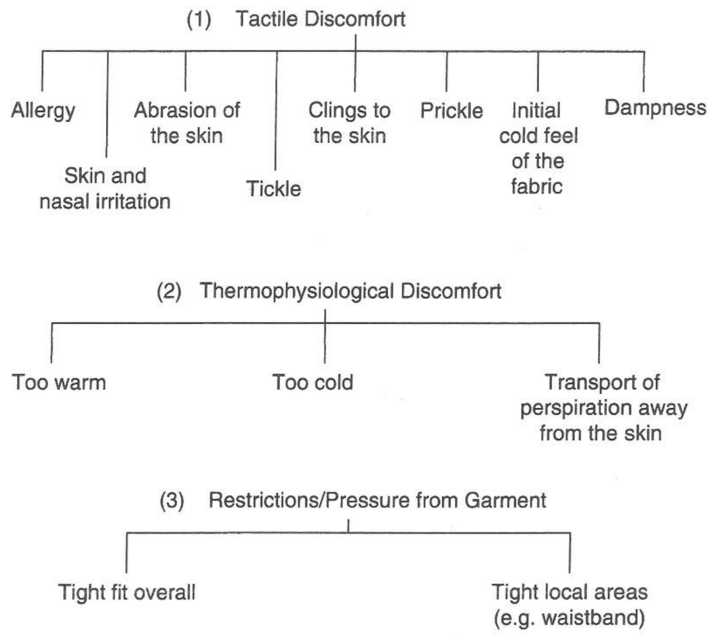
Fig. 4: Subjective Perception of Comfort (G. Song, 2011)

Many have attempted, but to date there is no universally accepted definition of comfort. In the Oxford English Dictionary and Webster's Third New International Dictionary, comfort is defined as ‘freedom from pain, trouble and anxiety, therefore comfort is a contented enjoyment in physical or mental well-being (Fan page 201). Slater (Fan page 202) defined comfort as a pleasant state of physiological, psychological and physical harmony between a human being and environment, classifying comfort into three interrelated aspects namely Physiological Comfort, Psychological Comfort and Physical Comfort.

PHYSIOLOGICAL COMFORT/DISCOMFORT:

The contribution of clothing towards thermal comfort is to enable the human body to maintain comfortable thermos-physiological conditions within an extended range of environments.

Smith (Fan and Hunter 2009) classified Physiological Discomfort Sensations in three categories, namely Sensorial (tactile) discomfort (what the fabric/garment feels like next to the skin), Thermo-physiological discomfort and Garment fit (body movement restrictions, pressure etc.). With respect to clothing physiological discomfort, **Figure 5**) classifies the different associated sensations (Fig. 8.1).



Classification of clothing physiological discomfort sensations. (Modified from Smith, 1986[3])

Fig 5: Classification of Clothing Physiological Discomfort Sensations (Fan in Fan and Hunter 2009)

Tactile sensations include allergies, skin and nasal irritations, skin abrasion, tickle, prickle, clinging (e.g. wet cling), initial contact (warm/cool) feeling, dampness/wetness etc. sensations.

Thermo-physiological comfort, often simply referred to as thermal comfort, was defined by ASHRAE as that condition of mind, which expresses satisfaction with the thermal environment (Ref. 26, page 244 of Fan and Hunter). The human being is a homeo-therm, meaning that the temperature of its central core must be maintained within narrow limits, various studies having shown that maintaining the core temperature within $37^o \pm 0.5^oC$ was vital for comfort and, in fact, survival, the maximum deviation of the core temperature, which can be tolerated, being about 2^oC from the normal level (i.e. $37^o \pm 2^oC$). Thermo-logical comfort is said to be achieved (Dolaz *et al, 2018*) when heat loss equals heat generation, resulting in the body keeping a constant temperature. Thermo-physiological comfort refers to the interaction between the body and the clothing, and involves the transport of heat and moisture from the body, through the clothing into the environment. Thermo-physiological sensations include coolness, warmth, chilling and sweating (Dolez *et al, 2018*). Rapid sweat transportation from the skin (e.g. through the fabric) leads to do better thermos-logical comfort.

The following textile properties influence thermal/thermo-physiological comfort (Dolez et al 2018):

- Water vapour resistance or breathability
- Thermal resistance (dry)
- Air permeability
- Liquid wicking rate
- Water resistance (under hydrostatic pressure)
- Water repellency

The relative importance of the above depends upon the specific application and function of the textile (e.g. office wear *vis-a vis* sportswear). It is perhaps worth noting that water is a good conductor of heat and can therefore greatly influence the heat (thermal) insulation of textile materials.

Ignoring extreme environmental conditions and psychological factors, probably the most important function of clothing is to provide thermo-physiological comfort to the wearer. This is largely determined by the thermal resistance (or insulation – R_t), moisture permeability (R_{et}) and liquid water transport of the clothing. In fact, virtually all laboratory/instrument related tests of fabric or clothing comfort simply measure one or more of the aforementioned properties, and then using the thermal resistance and moisture permeability to calculate the moisture permeability index (I_m) as follows:

$$I_m = 60.6 \times \frac{Rt}{Ret}$$

I_m is generally taken to provide a relative measure of the efficiency of moisture transmission, and is often also taken as a relative indication of comfort *per sé*.

Psychological Comfort

In addition to 'Physiological comfort, **Psychological Comfort** plays an important role in both the selection of clothing and the psychological well-being of the wearer. It is highly subjective, varying from one individual to another, from one culture to another, from one nationality to another, from one ethnical group to another etc. According to Fan (Fan and Hunter 2009), Psychological Comfort relates to the human mind's ability to function satisfactorily without external assistance. It is also defined as 'a pleasant state of psychological harmony' between the human being and the environment (Ref. 1 page 259 of Fan and Hunter). With regard to clothing, psychological comfort is the feeling that one is dressed in a style/fashion/manner, that is well in line with the purpose of the clothing and is in accord with one's view of one's economic, social and functional status *vis a vis* one's immediate work colleagues, or wider group of friends, associates and acquaintances (Ref. 4 page 259 of Fan and Hunter). In a sense. It relates to whether the clothing helps to boost (or enhance) one's self-image and self-esteem, also in the eyes of others and satisfies one's professional and personal/private standing and image, in line with that which one would like to project. **Figures 6 and 7** (in Fan and Hunter 2009) capture some of the above aspects.

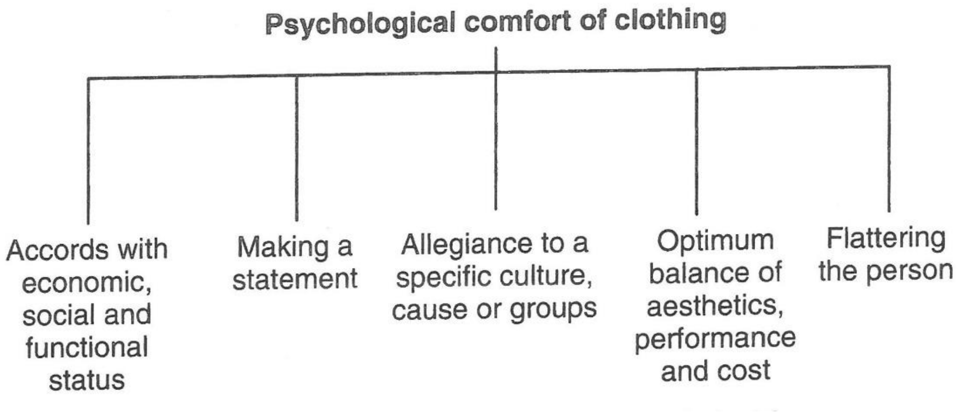


Fig. 6: Factors Related to the Psychological Comfort of Clothing

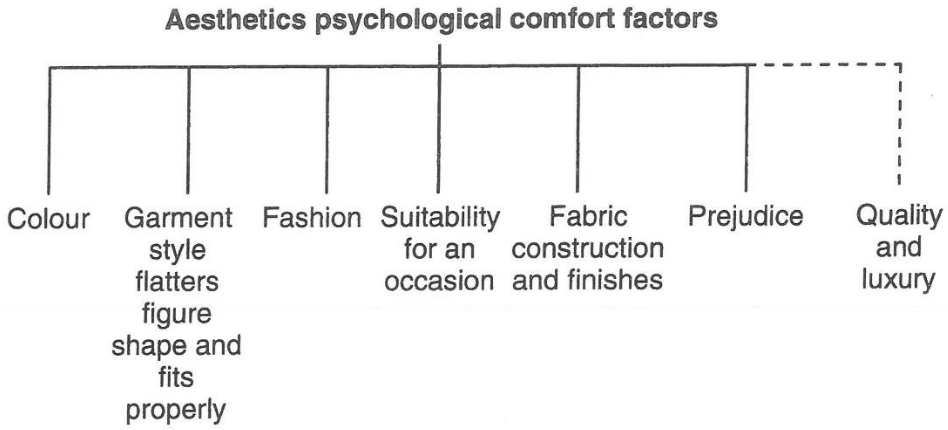


Fig. 7: Aesthetic Factors Related to Psychological Comfort

Being highly subjective and variable, **involving aspects such as adornment, fashion, status and modesty**, Psychological Comfort is extremely difficult to measure and quantify. Psychological scaling is often used for this purpose, assessing aspects such as colour emotions, body image and body catharsis (satisfaction with one’s own body), which are key indicators of psychological comfort. Fibre attributes and type can play an important role in respect of psychological comfort. For example, wearing rare and luxurious fibres, such as cashmere and silk, can boost the self-image and well- being, and even the perception of comfort of the wearer.

Aspects, such as garment design, sizing and fit as well as fashion and prejudice all play a role in the psychological comfort of fabrics and garments.

THE ASSESSMENT OF CLOTHING COMFORT:

Essentially, there are two main methods of assessing fabric and clothing comfort. The first, namely wear assessment or wearer trials, involves human subjects and monitoring (recording) their subjective assessment of the clothing and their physiological responses (e.g. heart and breathing rate, body temperature, perspiration etc.) This is normally done under different physical activities and environmental conditions, sometimes in a laboratory, for example, or under normal every-day and uncontrolled activities and ambient conditions, or sometimes even in a laboratory. The second is by using an instrument or instruments, in a laboratory, under carefully controlled conditions. Nevertheless, it is important to emphasize that laboratory instruments or manikins, however, sophisticated they be, do not measure comfort directly, but rather measure physical properties, such as moisture and thermal resistance, which are related to comfort, and their results therefore need to be validated by means of wearer trials. The Hohenstan Institute in Germany developed a 5-level system (**Fig 8** (Scott, Umbach 1983) for the physiological evaluation of clothing (Scott-Umbach, 1983).

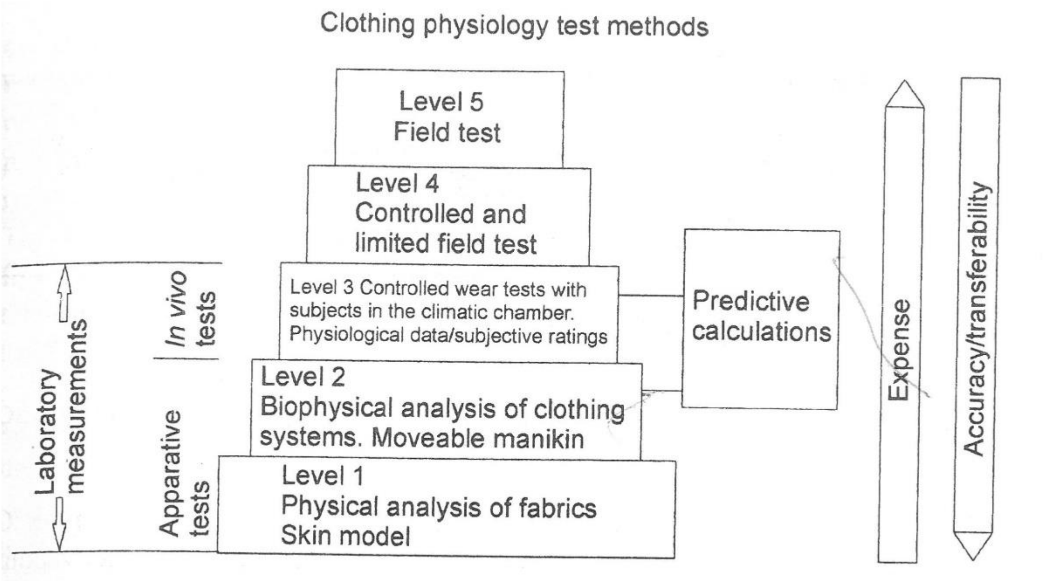


Figure 8: Five-level System of Physiological Evaluation of Clothing (Umbach, 1983)

The testing methods for the combined heat and moisture comfort of clothing are far more complex than for other fabric properties. To assess the heat and moisture comfort of fabrics or clothing ensembles, it is necessary to consider the human body, clothing, environment and other relevant factors. Broadly speaking, three methods are available for assessing the combined and moisture related comfort characteristics of clothing ensembles namely:

i. Micro-climate (heat and moisture transmission/resistance) method for fabrics;
ii. Thermal manikin with sweating skin and
iii. Wearer trials.

The latter being largely a subjective method. In actual wear conditions, the transmission of heat and moisture through the clothing takes place under a steady state as well as transient conditions.

There are broadly speaking two different instrumental measurement techniques for measuring the thermo-physiological properties of textiles, the dealing with fabrics (e.g. sweating guarded hot plate) and the other with garments and clothing ensembles (e.g. thermal sweating manikins) :

The one, which is the more traditional one, is by measuring the heat and water vapour transmission of fabrics and layers of fabrics, using the appropriate instruments. The other, and more recent one, is by using thermal (sweating) manikins, most of the latest manikins enabling both thermal insulation and water vapour transmission to be monitored, often under different atmospheric conditions and manikin positions and activities (e.g. stationary, walking, running etc.). These different approaches and methods will be now discussed briefly within the specific context of this review.

There are a number of instruments and test methods for measuring the thermal resistance or insulation of fabrics or fabric assemblies, such as the Gaurded Hot Plate, KESF Thermo-Labo-II and Alambeta instruments. For clothing, the thermal insulation properties of garments or clothing ensembles are increasingly being measured by using heated thermal manikins, of which a large number have been developed since 1945 (see **Table 2**, Holmér, 2004).

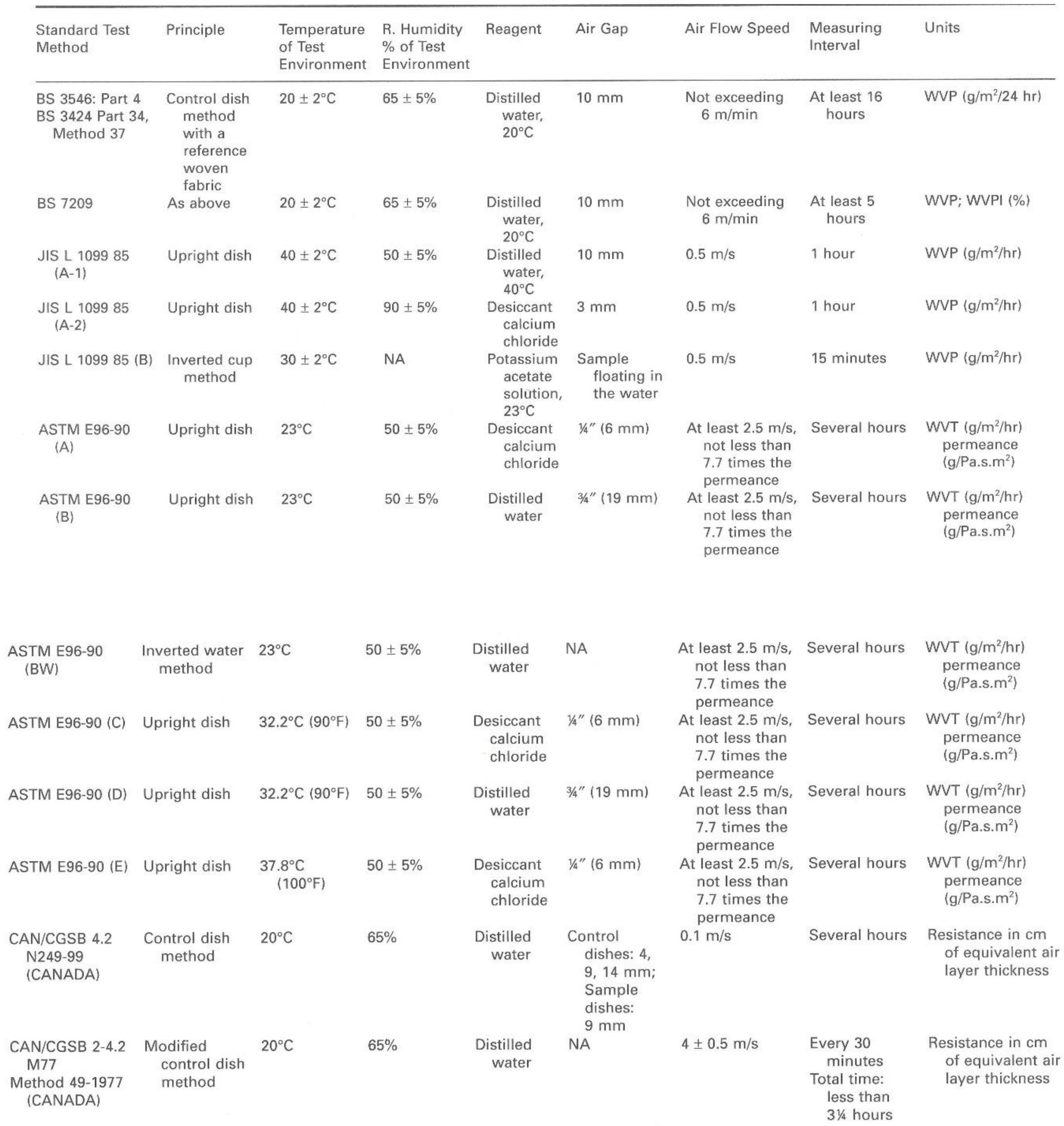
Table 2: Summary of the History of Thermal Manikins

(HOLMÉR, 2004) ***This table has been modified from the original***

1	One-segment	Copper		Analogue	USA 1945
2	Multi-segment	Aluminium		Analogue	UK 1964
3	Radiation manikin	Aluminium		Analogue	France 1972
4	Multi-segment	Plastics	Movable	Analogue	Denmark 1973
5	Multi-segment	Plastics	Movable	Analogue	Germany 1978
6	Multi-segment	Plastics	Movable	Digital	Sweden 1980
7	Multi-segment	Plastics	Movable	Digital	Sweden 1984
8	Fire manikin	Aluminium		Digital	USA
9	Immersion manikin	Aluminium	Movable	Digital	Canada 1988
10	Sweating manikin	Aluminium		Digital	Japan 1988
		Plastic	Movable	Digital	Finland 1988 (Coppelius)
		Aluminium	Movable	Digital	USA 1996
11	Female manikin	Plastics Single wire	Movable	Digital, comfort regulation mode	Denmark 1989
12	Breathing thermal manikin	Plastics Single wire	Movable, breathing simulation	Digital, comfort regulation mode	Denmark 1996
13	Sweating manikin	Plastic	Realistic movements	Digital, 30 dry and 125 sweat zones	Switzerland 2001 (SAM)
14	Self-contained, sweating field manikin	Metal	Articulated	Digital, 126 zones	USA 2003 (ADAM)
15	Virtual, computer manikin	Numerical, geometric model	Articulated	Heat and mass transfer simulations	China 2000 UK 2001 Sweden 2001 Japan 2002
16	One-segment, sweating manikin	Breathable fabric	Movable	Digital, water heated	China 2001 (Walter^{TM})
17	One-segment manikin	Windproof fabric	Movable	Digital, air heated	USA 2003

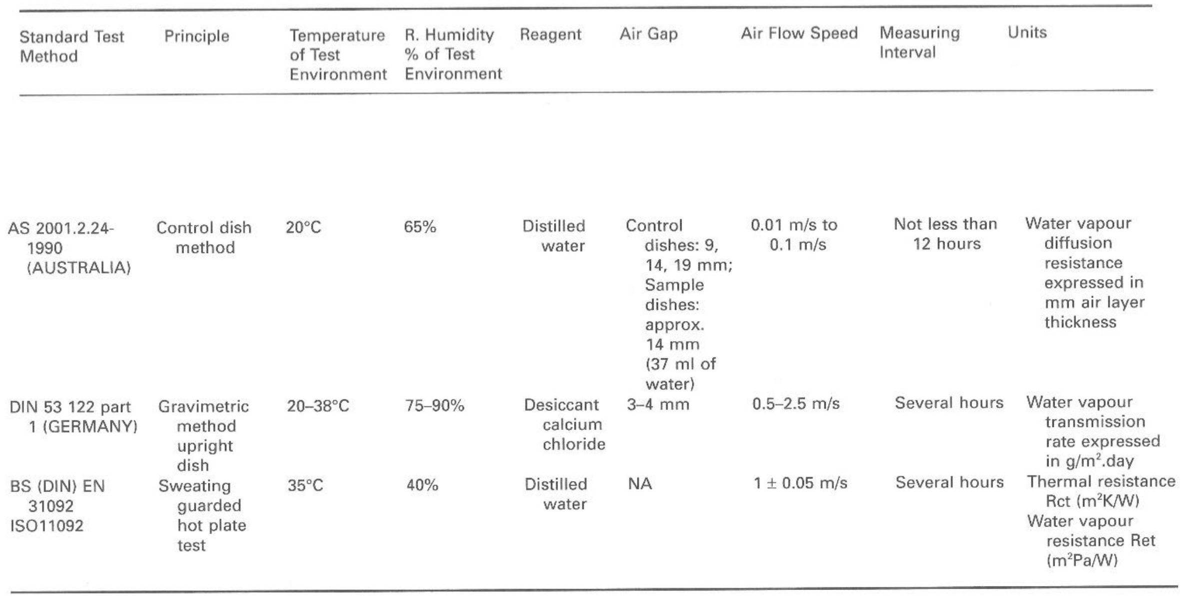
There are various standard test methods for measuring the water vapour permeability of fabrics (**Table 3**, Fan and Hunter, 2009 Ref. 73 2009).

Table 3: Summary of Current Standard Testing Methods for Water Vapour Permeability



Standard Test Method	Principle	Temperature of Test Environment	R. Humidity % of Test Environment	Reagent	Air Gap	Air Flow Speed	Measuring Interval	Units
BS 3546: Part 4 BS 3424 Part 34, Method 37	Control dish method with a reference woven fabric	20 ± 2°C	65 ± 5%	Distilled water, 20°C	10 mm	Not exceeding 6 m/min	At least 16 hours	WVP (g/m^2/24 hr)
BS 7209	As above	20 ± 2°C	65 ± 5%	Distilled water, 20°C	10 mm	Not exceeding 6 m/min	At least 5 hours	WVP; WVPI (%)
JIS L 1099 85 (A-1)	Upright dish	40 ± 2°C	50 ± 5%	Distilled water, 40°C	10 mm	0.5 m/s	1 hour	WVP (g/m^2/hr)
JIS L 1099 85 (A-2)	Upright dish	40 ± 2°C	90 ± 5%	Desiccant calcium chloride	3 mm	0.5 m/s	1 hour	WVP (g/m^2/hr)
JIS L 1099 85 (B)	Inverted cup method	30 ± 2°C	NA	Potassium acetate solution, 23°C	Sample floating in the water	0.5 m/s	15 minutes	WVP (g/m^2/hr)
ASTM E96-90 (A)	Upright dish	23°C	50 ± 5%	Desiccant calcium chloride	¼″ (6 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m^2/hr) permeance (g/Pa.s.m^2)
ASTM E96-90 (B)	Upright dish	23°C	50 ± 5%	Distilled water	¾″ (19 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m^2/hr) permeance (g/Pa.s.m^2)
ASTM E96-90 (BW)	Inverted water method	23°C	50 ± 5%	Distilled water	NA	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m^2/hr) permeance (g/Pa.s.m^2)
ASTM E96-90 (C)	Upright dish	32.2°C (90°F)	50 ± 5%	Desiccant calcium chloride	¼″ (6 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m^2/hr) permeance (g/Pa.s.m^2)
ASTM E96-90 (D)	Upright dish	32.2°C (90°F)	50 ± 5%	Distilled water	¾″ (19 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m^2/hr) permeance (g/Pa.s.m^2)
ASTM E96-90 (E)	Upright dish	37.8°C (100°F)	50 ± 5%	Desiccant calcium chloride	¼″ (6 mm)	At least 2.5 m/s, not less than 7.7 times the permeance	Several hours	WVT (g/m^2/hr) permeance (g/Pa.s.m^2)
CAN/CGSB 4.2 N249-99 (CANADA)	Control dish method	20°C	65%	Distilled water	Control dishes: 4, 9, 14 mm; Sample dishes: 9 mm	0.1 m/s	Several hours	Resistance in cm of equivalent air layer thickness
CAN/CGSB 2-4.2 M77 Method 49-1977 (CANADA)	Modified control dish method	20°C	65%	Distilled water	NA	4 ± 0.5 m/s	Every 30 minutes Total time: less than 3¼ hours	Resistance in cm of equivalent air layer thickness

Table 3 (continue)



Standard Test Method	Principle	Temperature of Test Environment	R. Humidity % of Test Environment	Reagent	Air Gap	Air Flow Speed	Measuring Interval	Units
AS 2001.2.24-1990 (AUSTRALIA)	Control dish method	20°C	65%	Distilled water	Control dishes: 9, 14, 19 mm; Sample dishes: approx. 14 mm (37 ml of water)	0.01 m/s to 0.1 m/s	Not less than 12 hours	Water vapour diffusion resistance expressed in mm air layer thickness
DIN 53 122 part 1 (GERMANY)	Gravimetric method upright dish	20–38°C	75–90%	Desiccant calcium chloride	3–4 mm	0.5–2.5 m/s	Several hours	Water vapour transmission rate expressed in g/m^2.day
BS (DIN) EN 31092 ISO11092	Sweating guarded hot plate test	35°C	40%	Distilled water	NA	1 ± 0.05 m/s	Several hours	Thermal resistance Rct (m^2K/W) Water vapour resistance Ret (m^2Pa/W)

A mannequin of manikin is, in its traditional (original) sense, a life-size model used by tailors, dressmakers, artists and window dressers to display or fit clothing (Nayak and Padhye 2017). Nevertheless, in a more modern and technical or scientific context, ‘manikin’ refers to a life-size anatomical model, often fitted with movable parts and/or sensors for specific applications, including teaching aids (simulators) for medical, arts or engineering students, evaluation of clothing comfort related thermal and evaporative resistance (comfort) and protection against external hazards, e.g. extreme weather (e.g. temperature) conditions, fire, (also flash fires), blasts (even nuclear), auto accidents etc. Probably, most manikins are designed and used to evaluate clothing comfort, such manikins being referred to as ‘thermal manikins’ enabling both thermal and evaporative resistance to be evaluated, often under widely different external conditions.

Within this the context of this review, only ‘thermal’ (or thermo-physiological) manikins are of interest, they being a ‘human form’ designed and used for evaluating the comfort related properties, of namely thermal and water vapour resistance (thermo-physiological comfort), of clothing and clothing ensembles under different environmental conditions, thereby avoiding the inherent subjective element , when using human subjects. Thermal manikins have been used in this capacity for almost a century (Nayak and Padhye) with the more recent advances in computer and sensor related technologies (including activators and simulation tools) enabling much better and realistic evaluation and modelling of the interaction between the human being and the external environment, and the role of clothing in this respect. **Table 4** captures Milestones in the development of thermal manikins.

Each example in the table represents a substantial improvement in the manikin (Wyon 1989). Holmér and Nilsson (1995), Holmér (2000) and McCullough (2005) have reviewed published work related to thermal manikins.

The ***clo***, a measure of the thermal insulation of clothing, was first introduced in 1941 (Gagge, Burton and Basset, 1941), which necessitated a method for its measurement, hence the development of the first thermal manikin in the United States (Belding, 1949).

The development of manikins can be grouped into three broad generations (categories): The first generation being standing or static (immovable) and non-perspiring, the second generation being movable but still non-perspiring and the third generation being movable and perspiring (e.g. Fan and Chen, 2002), the most advanced ones containing more than 20 independently (e.g. heat) controlled segments, some e.g. (Walter ^{TM}), even containing an interchangeable, ‘breathable’ type of skin which can more accurately mimic the human skin. Thermal manikins mimic the thermal interaction of the human body with its environment, the complexity of which increases when body movements and/or perspiration conditions are simulated. More than 100 manikins of various designs and functionalities are manufactured, worldwide.

Thermal manikins essentially comprise outer skin heating elements (e.g. water) and sensors. The use of thermal manikins for evaluating clothing comfort is increasing, largely as a result of their accuracy and repeatability in generating more realistic results and modelling. Basically, only the following seven different types of thermal manikins are widely accepted:

1. Coppeluis – Finnish
2. TARO-Japanese
3. KEM – Japanese
4. Newton – United States of America
5. SAM – Swiss
6. Walter – Hong Kong
7. ADAM – United States of America

The recent thermal manikins are mainly used in the following three major areas (Holmér, 2004).

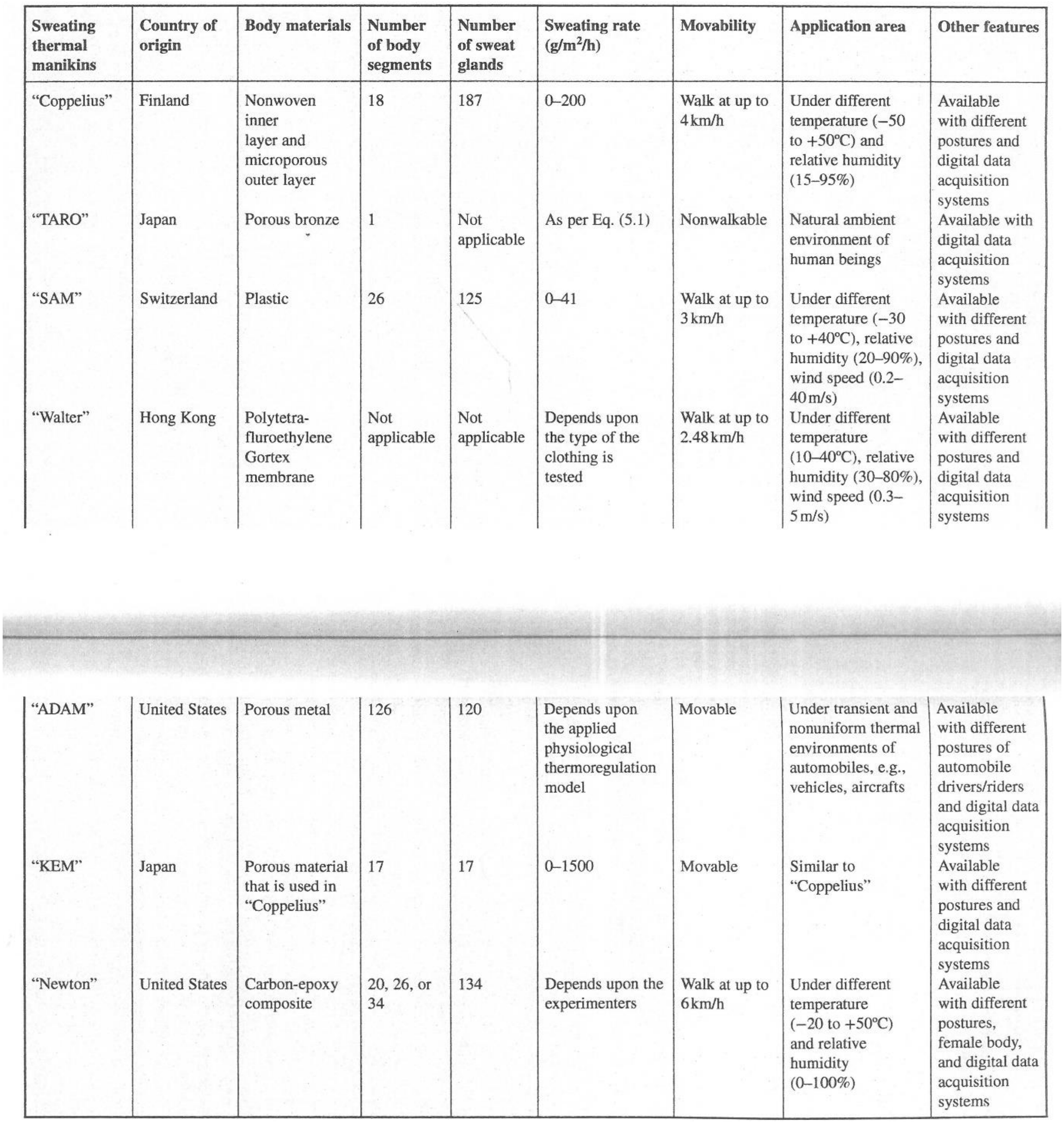
- To evaluate the heat transfer characteristics of clothing.
- To evaluate the effect of thermal environments on the human body.
- To evaluate the effectiveness of heating, ventilation and air conditioning (HVAC).

All the above is from Nayak and Padhye. Manikins can be used for both wet and dry tests. The thermal resistance of wet clothing or fabric is much lower than that of dry clothing or fabric, hence the important role of perspiration in this regard.

Zuo and McCullough (2004 in Nayak and Padhye) found that the evaporative resistance of a variety of permeable and impermeable protective clothing ensembles used in certain sports wear (e.g. football, baseball. soccer and tennis) depended upon the moisture permeability and wicking properties of the fabrics, with the fibre content of the fabrics having little effect. Fabric structure and surface finish greatly affected the moisture permeability, open structures being more moisture permeable than compact (tight) structures. Thicker fabrics generally have a higher evaporative resistance than thinner fabrics.

The following are significant performance features of thermal manikins.

Table 4: Significant Performance Features of Thermal Manikins (Holmé, I, 2004, Thermal manikin history and Applications, European Journal of Applied Physiology, 92(6), 614-618).



Sweating thermal manikins	Country of origin	Body materials	Number of body segments	Number of sweat glands	Sweating rate ($g/m^2/h$)	Movability	Application area	Other features
“Coppelius”	Finland	Nonwoven inner layer and microporous outer layer	18	187	0–200	Walk at up to 4 km/h	Under different temperature (−50 to +50°C) and relative humidity (15–95%)	Available with different postures and digital data acquisition systems
“TARO”	Japan	Porous bronze	1	Not applicable	As per Eq. (5.1)	Nonwalkable	Natural ambient environment of human beings	Available with digital data acquisition systems
“SAM”	Switzerland	Plastic	26	125	0–41	Walk at up to 3 km/h	Under different temperature (−30 to +40°C), relative humidity (20–90%), wind speed (0.2–40 m/s)	Available with different postures and digital data acquisition systems
“Walter”	Hong Kong	Polytetra-fluroethylene Gortex membrane	Not applicable	Not applicable	Depends upon the type of the clothing is tested	Walk at up to 2.48 km/h	Under different temperature (10–40°C), relative humidity (30–80%), wind speed (0.3–5 m/s)	Available with different postures and digital data acquisition systems
“ADAM”	United States	Porous metal	126	120	Depends upon the applied physiological thermoregulation model	Movable	Under transient and nonuniform thermal environments of automobiles, e.g., vehicles, aircrafts	Available with different postures of automobile drivers/riders and digital data acquisition systems
“KEM”	Japan	Porous material that is used in “Coppelius”	17	17	0–1500	Movable	Similar to “Coppelius”	Available with different postures and digital data acquisition systems
“Newton”	United States	Carbon-epoxy composite	20, 26, or 34	134	Depends upon the experimenters	Walk at up to 6 km/h	Under different temperature (−20 to +50°C) and relative humidity (0–100%)	Available with different postures, female body, and digital data acquisition systems

There are essential two broad categories of manikins, namely static (usually standing) and dynamic or movable, which have joints allowing movement (e.g. simulating sitting, walking, running, cycling etc.). A manikin can in some respects, be classified as a ‘virtual or digital human model’.

It has been concluded (Pamuk O., Abreu, M.J. and Öndoğan, Z., Tekstil ve Konfeksiyon, **18**(3), 236-239, 2008) that thermal manikins were necessary instruments for measuring the thermal insulation, thermal resistance and heat loss of the clothing system, these being important parameters in terms of clothing thermal comfort (Nayak and Padhye 2017).

Comparison of manikin tests and wearer trials.

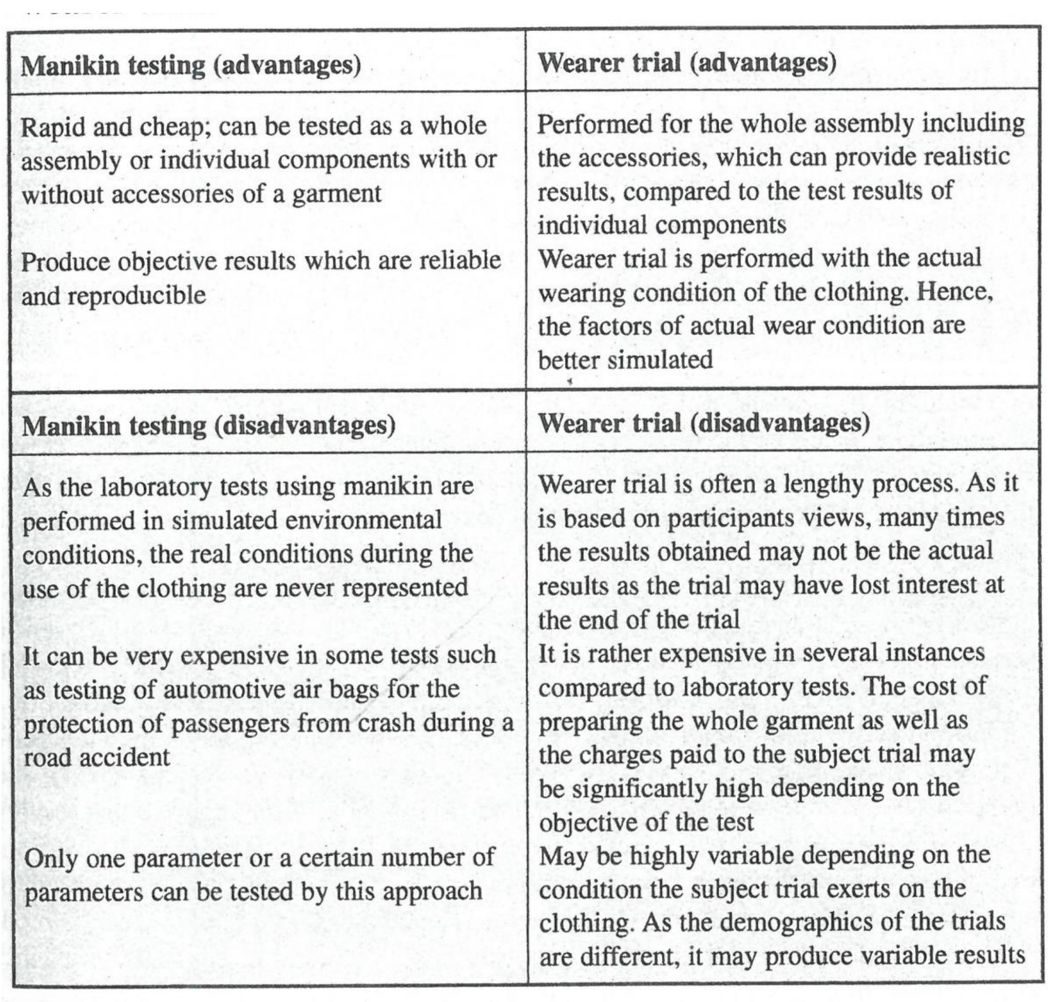
The comfort related properties of textiles can be evaluated at the fabric stage (usually in a laboratory, using laboratory instruments) and at the garment or clothing stages, using either thermal manikins (in a laboratory) or wearer trials (under ‘field’ conditions and/or controlled conditions in a laboratory).

This section deals with published studies in which the results of manikin tests and wearer trials have been compared. Wearer trials are mostly a very long, complicated and costly process, often involving many months of wear (if not years), different subjects and different external (environmental) conditions. The design and use of manikins are aimed at simulating the human body as closely as possible in terms of heat and sweat generation and movement.

Generally, garment/clothing wearer trials involve one or more wearers wearing the clothing or garment under either controlled laboratory or ambient (field) conditions, closely resembling the conditions (i.e. actual) under which the clothing would normally be worn, and then noting, at regular pre-determined intervals, the wearer’s perceptions/impressions and in some cases even monitoring the physiological responses (e.g. breathing, pulse rate, temperature and blood pressure) of the wearer.

Nayak and Padhye (2017) summarised the relative advantages and disadvantages of manikin testing *vis-a-vis* wearer trials (**Table 5**, Nayak and Padhye 2017 page 166).

Table 5: Advantages and Disadvantages of Manikin Testing and Wearer Trials



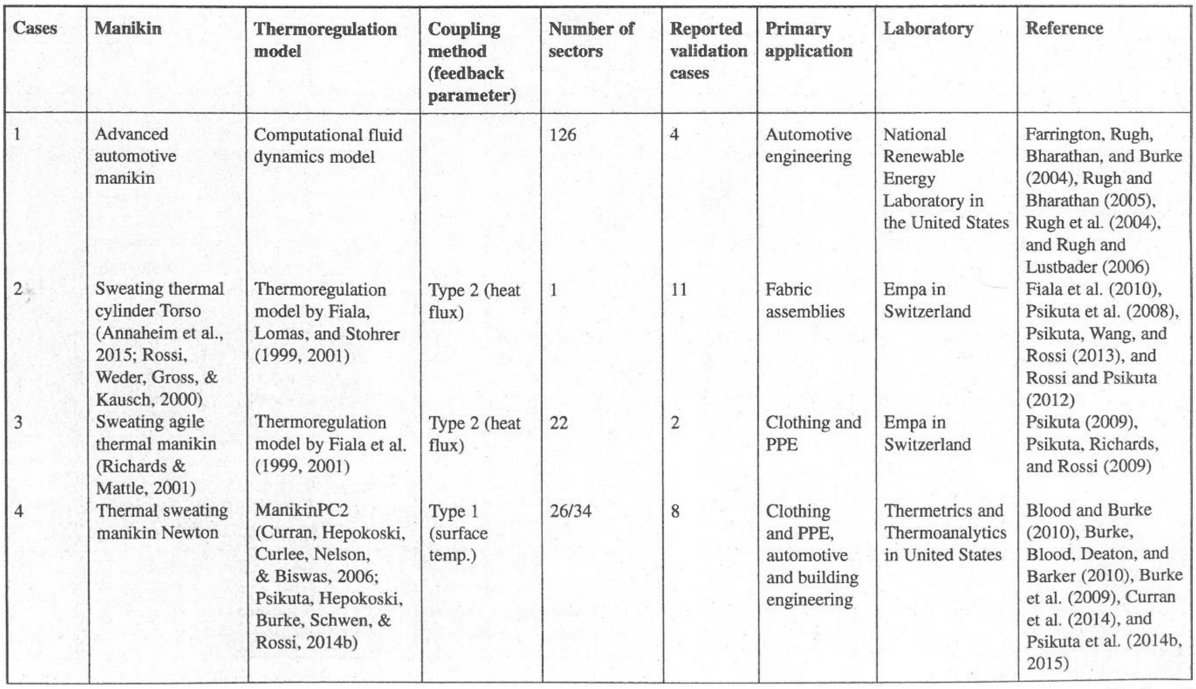
Manikin testing (advantages)	Wearer trial (advantages)
Rapid and cheap; can be tested as a whole assembly or individual components with or without accessories of a garment	Performed for the whole assembly including the accessories, which can provide realistic results, compared to the test results of individual components
Produce objective results which are reliable and reproducible	Wearer trial is performed with the actual wearing condition of the clothing. Hence, the factors of actual wear condition are better simulated
Manikin testing (disadvantages)	**Wearer trial (disadvantages)**
As the laboratory tests using manikin are performed in simulated environmental conditions, the real conditions during the use of the clothing are never represented	Wearer trial is often a lengthy process. As it is based on participants views, many times the results obtained may not be the actual results as the trial may have lost interest at the end of the trial
It can be very expensive in some tests such as testing of automotive air bags for the protection of passengers from crash during a road accident	It is rather expensive in several instances compared to laboratory tests. The cost of preparing the whole garment as well as the charges paid to the subject trial may be significantly high depending on the objective of the test
Only one parameter or a certain number of parameters can be tested by this approach	May be highly variable depending on the condition the subject trial exerts on the clothing. As the demographics of the trials are different, it may produce variable results

Manikins have been designed for various functional applications and evaluations, such as for:

1) Pressure assessment 2) Medical textile evaluation 3) Thermo-physiological Comfort assessment 4) Defence applications 5) Automotive Applications 6) Drape evaluation 7) Steam and Hot Liquid splash evaluation 8) Flame and Flash Fire Protection 9) Clothing Size and Fit
10) Evaluation of Ergonomics (fit and freedom of movement).

Table 6 (Nayak and Padhye, 2017) summarises the thermo-physiological human simulators developed over the years.

Table 6: Summary of the Thermo-physiological Human Simulators Developed 'Up to Date'.



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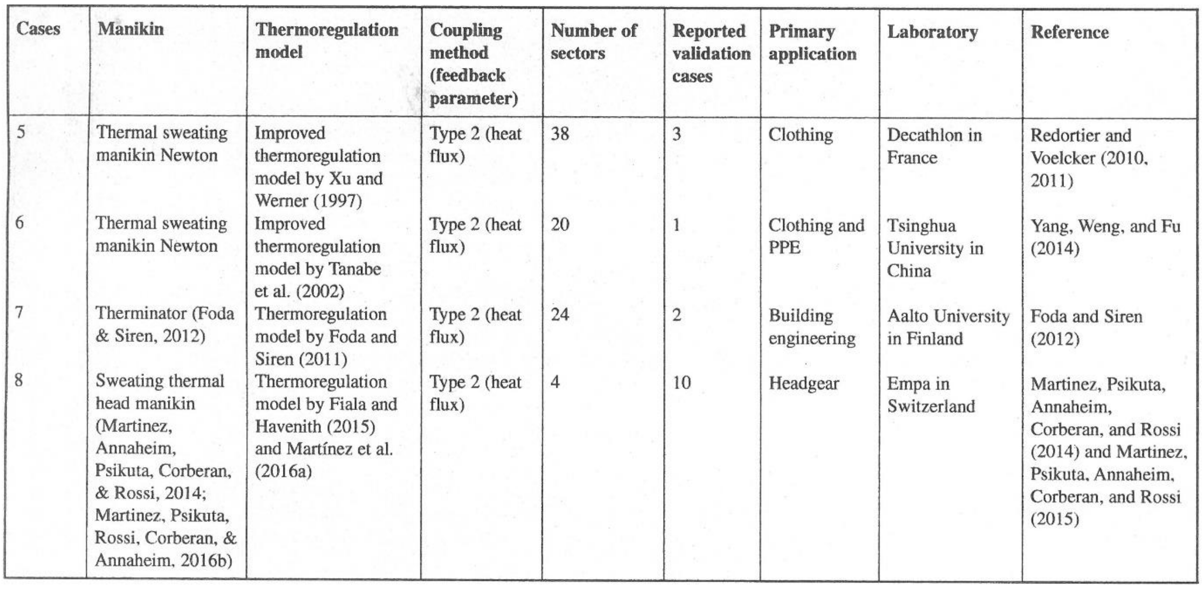


Cases	Manikin	Thermoregulation model	Coupling method (feedback parameter)	Number of sectors	Reported validation cases	Primary application	Laboratory	Reference
1	Advanced automotive manikin	Computational fluid dynamics model		126	4	Automotive engineering	National Renewable Energy Laboratory in the United States	Farrington, Rugh, Bharathan, and Burke (2004), Rugh and Bharathan (2005), Rugh et al. (2004), and Rugh and Lustbader (2006)
2	Sweating thermal cylinder Torso (Annaheim et al., 2015; Rossi, Weder, Gross, & Kausch, 2000)	Thermoregulation model by Fiala, Lomas, and Stohrer (1999, 2001)	Type 2 (heat flux)	1	11	Fabric assemblies	Empa in Switzerland	Fiala et al. (2010), Psikuta et al. (2008), Psikuta, Wang, and Rossi (2013), and Rossi and Psikuta (2012)
3	Sweating agile thermal manikin (Richards & Mattle, 2001)	Thermoregulation model by Fiala et al. (1999, 2001)	Type 2 (heat flux)	22	2	Clothing and PPE	Empa in Switzerland	Psikuta (2009), Psikuta, Richards, and Rossi (2009)
4	Thermal sweating manikin Newton	ManikinPC2 (Curran, Hepokoski, Curlee, Nelson, & Biswas, 2006; Psikuta, Hepokoski, Burke, Schwen, & Rossi, 2014b)	Type 1 (surface temp.)	26/34	8	Clothing and PPE, automotive and building engineering	Thermetrics and Thermoanalytics in United States	Blood and Burke (2010), Burke, Blood, Deaton, and Barker (2010), Burke et al. (2009), Curran et al. (2014), and Psikuta et al. (2014b, 2015)
5	Thermal sweating manikin Newton	Improved thermoregulation model by Xu and Werner (1997)	Type 2 (heat flux)	38	3	Clothing	Decathlon in France	Redortier and Voelcker (2010, 2011)
6	Thermal sweating manikin Newton	Improved thermoregulation model by Tanabe et al. (2002)	Type 2 (heat flux)	20	1	Clothing and PPE	Tsinghua University in China	Yang, Weng, and Fu (2014)
7	Therminator (Foda & Siren, 2012)	Thermoregulation model by Foda and Siren (2011)	Type 2 (heat flux)	24	2	Building engineering	Aalto University in Finland	Foda and Siren (2012)
8	Sweating thermal head manikin (Martinez, Annaheim, Psikuta, Corberan, & Rossi, 2014; Martinez, Psikuta, Rossi, Corberan, & Annaheim, 2016b)	Thermoregulation model by Fiala and Havenith (2015) and Martínez et al. (2016a)	Type 2 (heat flux)	4	10	Headgear	Empa in Switzerland	Martinez, Psikuta, Annaheim, Corberan, and Rossi (2014) and Martinez, Psikuta, Annaheim, Corberan, and Rossi (2015)

Thermo-physiological human simulators aim at handling and evaluating more complex situations than is possible by means of thermal manikins, the latter assessing the heat transfer properties but not the human thermal response and simulation of local thermos-physiological reactions and modelling, which the former does.

There are two major areas of application of manikins, namely determining clothing heat and mass (liquid/vapour) transfer characteristics and the assessment of the impact of extreme thermal environments/environments (e.g. flame, fire, hot liquids and steam etc.) on the body.

A thermal manikin acts as a human body shaped sensor, and measures convective, radiant and conductive heat losses from the whole manikin (body) or from local segments of the body.

The body loses heat through conductive, convective and radiant heat exchange with the environment and by the evaporation of sweat. The heat is lost from the boy surface and through respiration (convection and evaporation) (Scott, Ed. 2010).

The Permeability Index (I_m) indicates the maximum evaporative heat transfer permitted by a clothing system as compared to the ideal maximum from an uncovered surface (i.e. a slung psychrometer) defined by Woodcock (1962) as:

$I_m = (R_t/R_{et})/LR$ (Scott, Chapter 9)

LR = Lewis relation, commonly given a value of 16.65°C/*kPa.*

I_m usually ranges from about 0.50 for a nude manikin to about 0.05 for an impermeable single-layer ensemble with a low thermal resistance and high evaporative resistance.

For a wide range of 'normal' clothing ensembles I_m typically ranges from about 0.37 to about 0,43, with chemically protective suits being ≈ 0.15.

Evaporative cooling is a very efficient means of heat dissipation, as one litre evaporated sweat removes 672 *Wh* from the body at a temperature of 35°C. (Chapter 9 Scott 2010).

The **liquid water transport properties,** related to the moisture absorption and wicking properties of fabrics, can generally be measured by four types of test methods, namely:

- Longitudinal Wicking 'strip' tests.
- Transverse (or trans-planar) Wicking plate tests.
- Areal Wicking 'spot' tests.
- Syphon tests.

Garment Fit and Ease of Body Movement:

Body movement is an essential part of human existence, and clothing, being the second skin of the human body, must both fit properly and enable the body to move without undue discomfort. It can be said that a well-fitted garment is one that is comfortable to wear, consistent with fashion and free of undesirable or unsightly wrinkles, sags or bulges, and which allows sufficient ease or freedom of movement (Refs 80, 125 on pages 247 and 249 of Fan and Hunter).

Wear Assessment:

Clothing wearer trials involve human subjects and are performed under actual wear conditions (field trials) or under appropriate controlled laboratory conditions.

Wear assessment, or wearer trials, are the most highly complex, difficult, time-consuming and expensive way of assessing clothing comfort, and by its very nature, highly subjective and prone to error. Human beings differ greatly in size, fitness, metabolic rate, and activity as well as their comfort and discomfort thresholds and perceptions with cultural background also playing an important role in the individual's perception of comfort. Nevertheless, it remains the standard or benchmark.

Thermal Insulation/Resistance

The human body loses heat in various ways (**Fig 9**) 2014 and it needs to be considered when attempting to measure, in a laboratory, the comfort related thermal-insulation of fabrics and clothing.

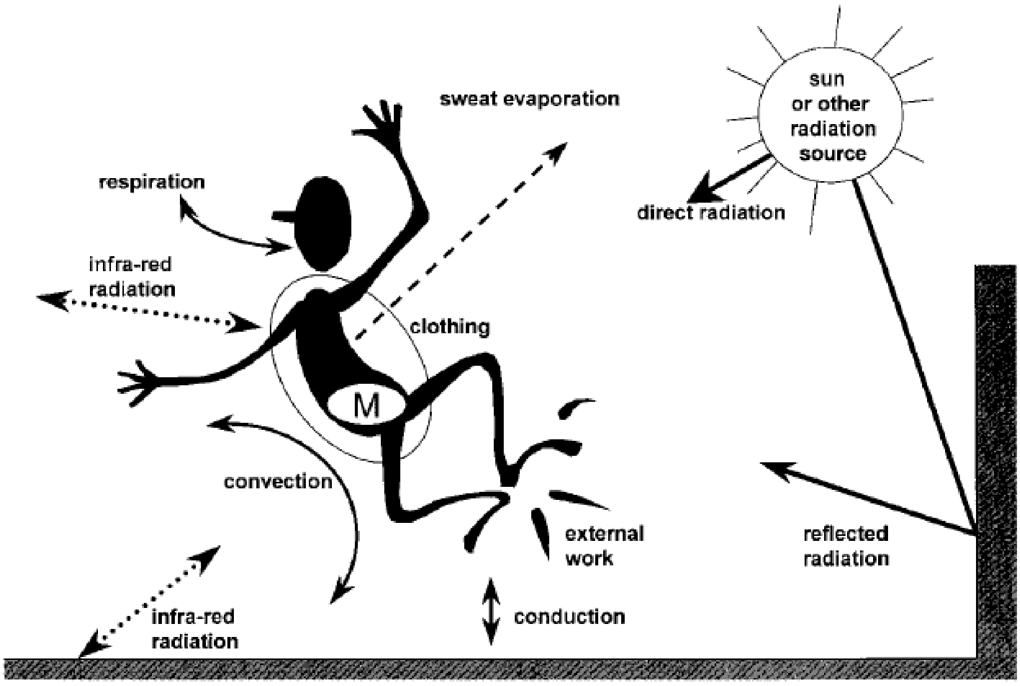


Fig. 9: Schematic Representation of the Loss of Heat from the Human Body (Stoffberg 2014)

The thermal comfort of a clothing system is associated with the thermal balance of the body and its thermo-regulatory responses to the dynamic interactions with the clothing and the environment (Das and Alagirusamy). Nevertheless, not only the heat but also the moisture transmission behaviour of a clothing ensemble plays a very important role in maintaining thermo-physiological comfort. The fabric should allow moisture, both in the form of sensible and insensible perspiration, to be transmitted from the body to the environment, so as to cool the body (latent heat of evaporation), and reduce the chances of a drop in the thermal insulation of the fabric (garment), due to the accumulation of moisture within the micro-climate region (Das and Alagirusamy). If the fabric in contact with the body is not dry, the heat flow from the body increases, resulting in an undesirable loss in body heat, and generally also a 'clammy feel'. Therefore, ideally, both the heat as well as moisture transmission of a fabric should be measured. The human body is rarely in a thermal steady state, but is rather continuously exposed to changing physical activity and environmental conditions (Das and Alagirusamy, 2010).

The thermal insulation properties of textile fabrics and clothing can be expressed in terms of thermal conductivity or thermal resistance. The thermal resistance (R_t) of a textile material is the temperature difference between the two faces of the material divided by the resultant heat flux per unit area in the direction of the gradient (ISO 11092, 2014). The ISO (SI) unit for thermal conductivity is *W/mK* and that for thermal resistance is Km^2/W. There are also two popularly used units for thermal resistance or insulation, namely the *Tog* and *clo*. A *Tog* is defined as the approximate insulation of light summer clothing (Fan and Hunter) with $1\ Tog = 0.1\ Km^2/W$ (BS 4745, 2005). The *clo* is defined as the insulation required to keep a resting person (producing heat at the rate of $58W/m^2$) comfortable in an environment of 21°C and air movement of 2.1m/s, or roughly, the insulation value of typical indoor clothing. It relates to the whole body, including the exposed parts.

$1\ clo = 1.55\ Togs = 0.155Km^2/W$

Thermal conductivity *k* (sometimes called λ) is related to the thermal resistance (R_{et} or R_t) as follows:

$K = L/R_t$

Where *L* is the material thickness

Thermal effusivity (*e*) can be calculated as follows:

$e = (k_{\rho} C_p)^{0.5}$,

where ρ is the density in $kg.m^3$ and C_p is the heat capacity (*J/kg.K*)

Several instruments are available for determining the thermal insulation properties of fabrics and fabric assemblies, including:

- Gaurded Hot Plate **(Fig. 10)** (Fan and Hunter, 2009)
- KESF Thermo Labo-II and
- Alambeta

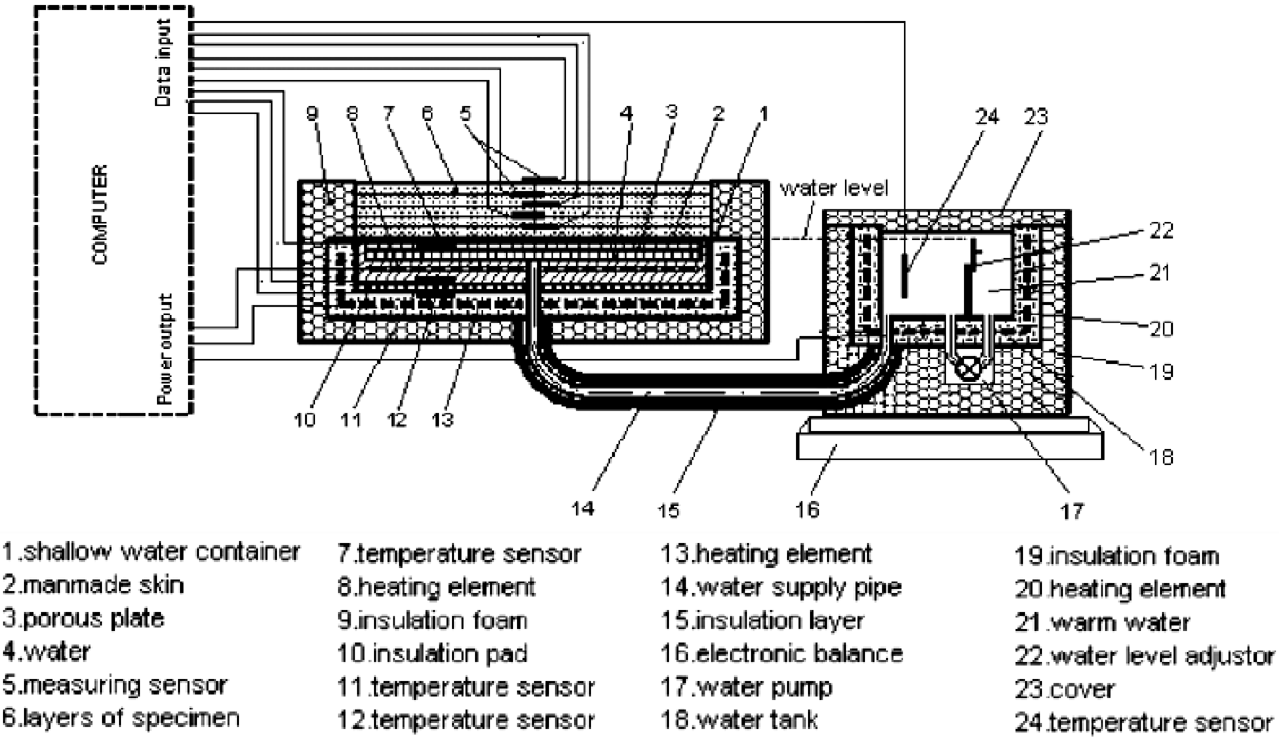


Fig. 10 Schematic of the Sweating Gaurded Hot Plate (Based on ISO 11092: 1993 (E)) (Britz 2017)

In essence, these instrumental methods determine the heat flux by measuring the energy required to maintain a set temperature of a heated device when it is covered by a textile fabric, as well as the temperature difference across the textile material, the thermal conductivity (k) being calculated as follows:

$k = \frac{W \times D}{\mathrm{A} \times \Delta \mathrm{T}}$ $(W/m.^{0}C)$

Where W is the heat flow, D is the fabric thickness, A is the area of the hot plate covered by the fabric and ΔT is the temperature difference across the fabric.

The thermal resistance; or insulation is:

$I = D/K = \frac{A \times \Delta T}{\mathrm{W}}$ (Km^{2}/W)

The thermal transmittance U is calculated as follow:

$U = \frac{W}{\mathrm{A} \times \Delta \mathrm{T}}$ $(W/m^{2}K)$

The Warmth Keepability Rating Q, is calculated as follows:

$Q = (1 - \frac{b}{a}) \times 100$, where a is the heat emanated from the blank 'emanator' or test plate (i.e. without the fabric test specimen in place) and b is the heat emanated from the emanator or test plate with the test specimen mounted.

THERMAL TRANSMISSION/RESISTANCE:

The following factors play a role in the thermal properties (i.e. heat transmission/resistance) of textile materials (Ukponmwan, 1993):

1. Thermal conductivity of the fibre and the air contained (entrapped) within the fabric.
2. Specific heat of the fibre substance.
3. Fabric thickness.
4. Fabric density.
5. Fabric surface (e.g. flat, brushed, fibrous, etc.).
6. Area of contact between fabric surface and body (affected in a similar way as 5).
7. Heat loss by conduction, skin to fabric.
8. Heat loss by convection, from the skin through fabric and from the fabric surface.

9. Heat loss by radiation.
10. Heat loss by evaporation of water/perspiration from skin or fabric.
11. Heat gain due to heat absorption by fibre.
12. Environmental factors (e.g. temperature, relative humidity, wind/air movement).

The heat loss from the human body was illustrated schematically in **Fig. 9** (Stoffberg 2014).

Effect of Fibre Type

In terms of heat/thermal insulation, the most important factor is the amount (volume) of air entrapped within the fabric, since the thermal resistance of air is more than double that of most fibres. There are, however, also some differences between the various fibres (**Fig. 11**; Stoffberg 2014), with the thermal conductivity of the natural fibres, notably wool and silk, significantly lower than that of the man-made fibres.

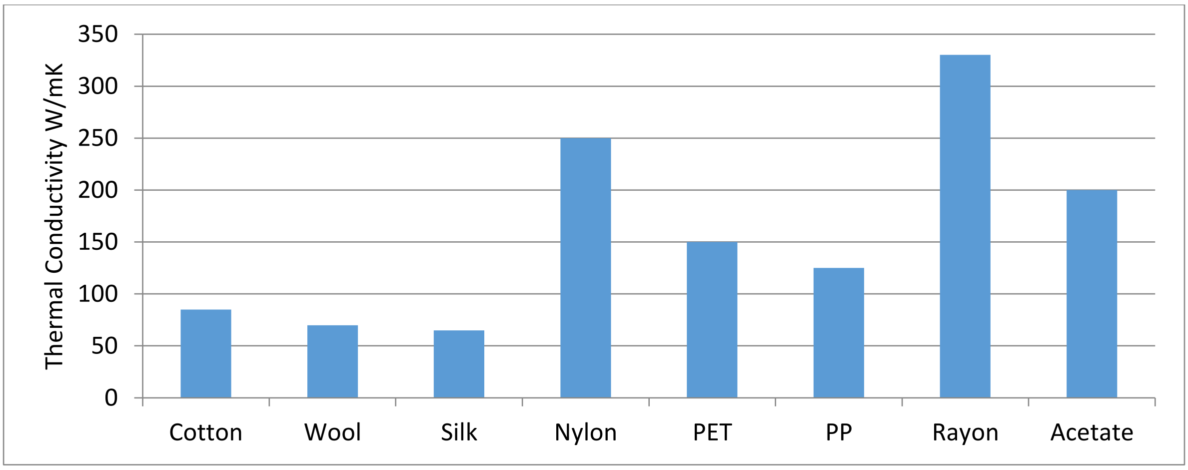
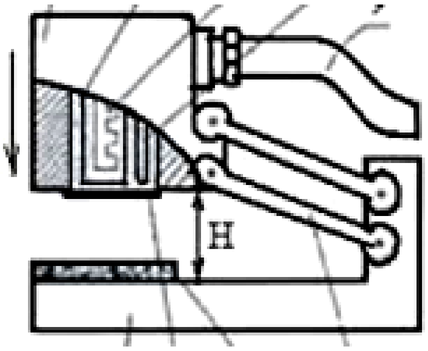


Fig. 11: Thermal Conductivity of Natural and Synthetic Fibres

From **Fig. 11** it can be seen that the thermal conductivity of the man-made fibres, notably rayon and nylon, is significantly higher, almost six times higher, than that of the natural fibres, notably wool and silk. Therefore, in terms of the fibre *per se*, ignoring any differences in factors, such as volume of air entrapped, wool should provide far better heat insulation than man-made fibres, such as polyester, nylon and regenerated fibres (viscose and rayon).

Various studies have been carried out in which the thermal insulating properties of fabrics, comprising different fibres and fibre types have been measured and compared. In many cases 'hot plate' type instruments were used for measuring the thermal resistance, many of the instruments also enabling the water vapour permeability to be measured. Two examples of the latter are the Alambeta (**Fig. 12**) and Permetest (**Fig. 13**).



1 - Measuring head

2 - Copper block

3 - Electric heater

4 - Heat flow sensor

5 - Measured sample

6 - Instrument base

7 - Head lifting mechanism

8 - Resistance thermometer

9 - Cable connecting measuring head with computer

Fig. 12: Schematic of the Alambeta (Britz 2017)

- Permetest

Fig. 13: Permetest Instrument (Britz 2017)

One study (Stoffberg, 2014 and Stoffberg *et al* 2014) used the Permetest to measure the thermal resistance and water vapour permeability of 26 commercial worsted suiting fabrics which differed in weave structure (plain, 2x2 twill and 2x1 twill), mass 145 to250g/m^2, thickness (0.23 to 0.65mm) and comprising different fibre types (wool, polyester, viscose and cotton) and their blends. From the thermal resistance (R_t) and the water (moisture) vapour permeability (R_{et}) she calculated the moisture permeability index (I_m) which is often taken as an overall measure of the thermo-physiological comfort of a fabric and clothing, as follows:

$$I_m = \frac{60.6Rt}{Ret}$$

Based upon multi-regression analysis of the results, she concluded that the role of the fabric parameters, mass and thickness in particular, had a far greater effect on the thermal resistance and water vapour permeability than the fibre type or blend. The most significant empirical linear relationships were found between fabric thermal resistance (R_t) and fabric thickness (**Fig. 14** Stoffberg 2014), fabric water vapour resistance (R_{et}) and fabric mass (**Fig. 15** Stoffberg), fabric water vapour permeability and fabric mass (**Fig. 16**; Stoffberg), and fabric moisture permeability index (I_m) and fabric air permeability (**Fig. 17**; Stoffberg), with neither fibre type nor blend appearing to have a significant effect on any of these parameters. Multi-quadratic regression analysis showed that fabric thickness, and to a much lesser extent fabric density, had statistically the most significant effects on fabric thermal resistance (heat insulation), the latter increasing as fabric mass and/or density increased.

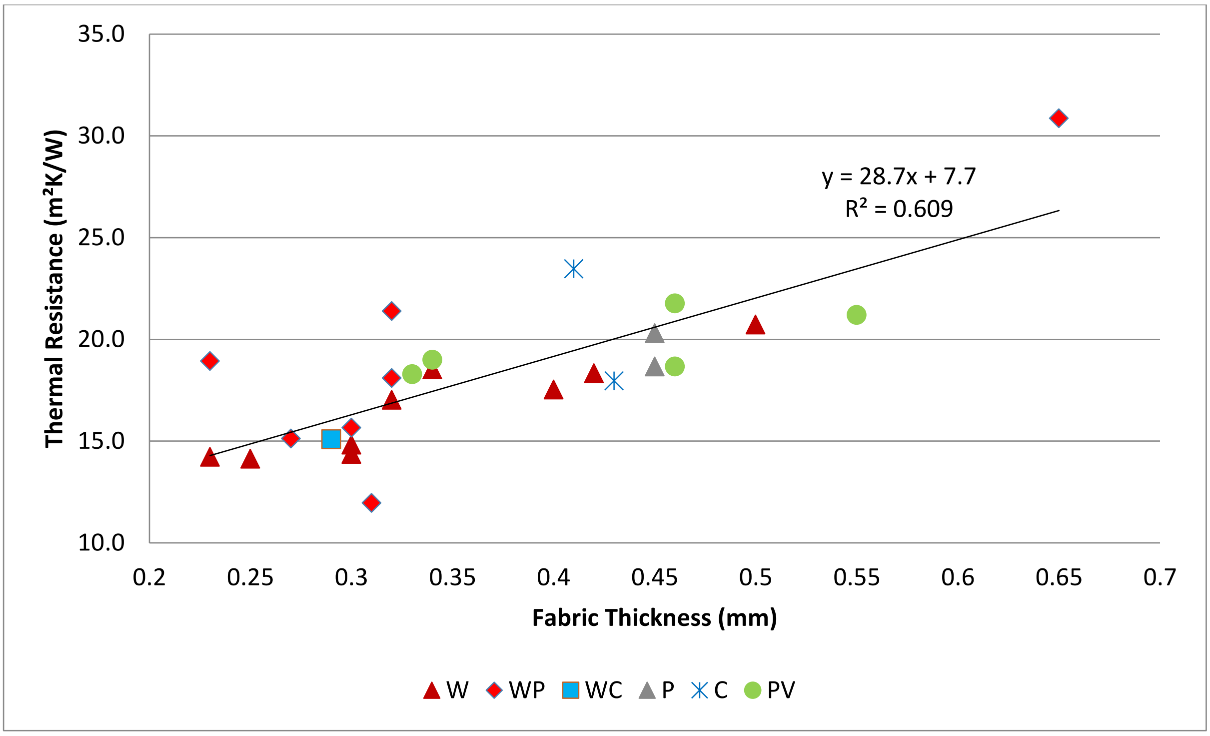


Fig.14: Thermal Resistance *versus* Fabric Thickness

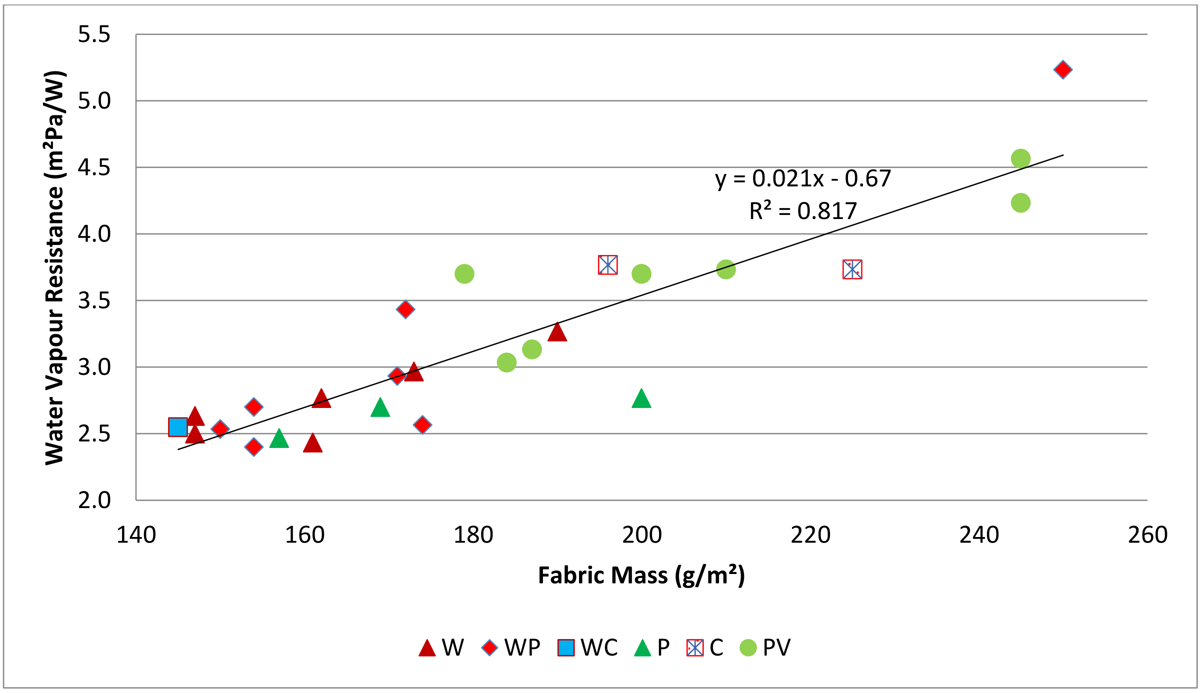


Fig. 15: Water Vapour Resistance *versus* Fabric Mass

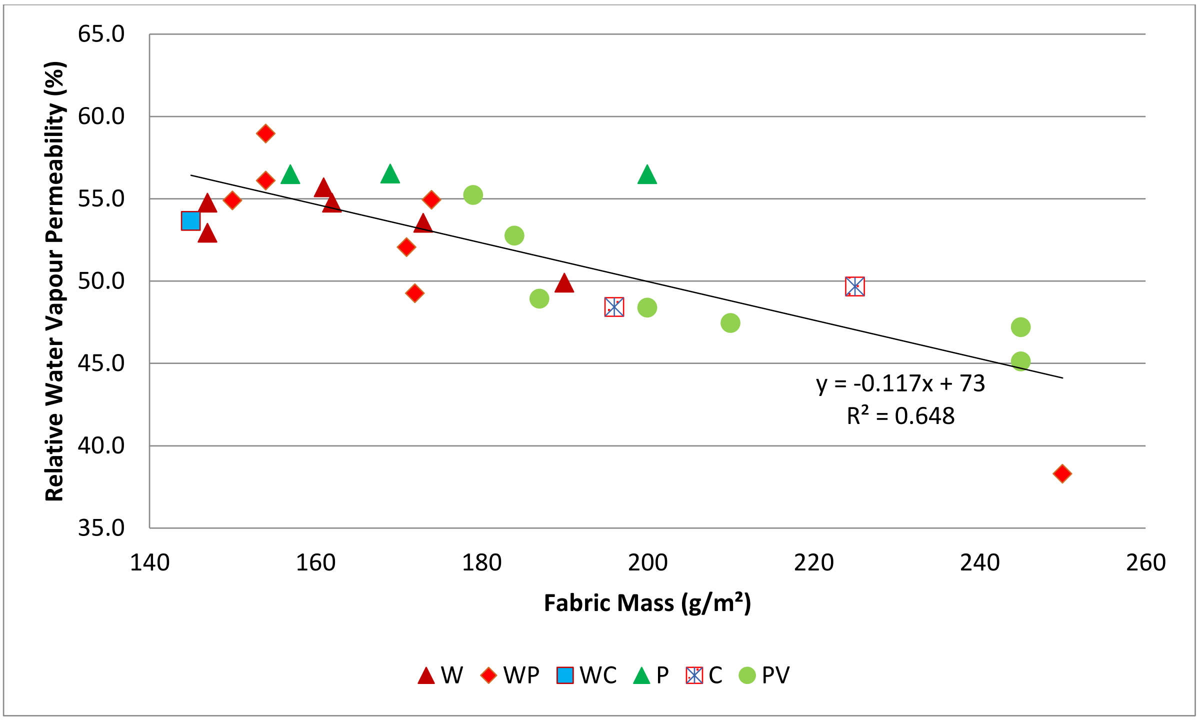


Fig. 16: Relative Water Vapour Permeability *versus* Fabric Mass

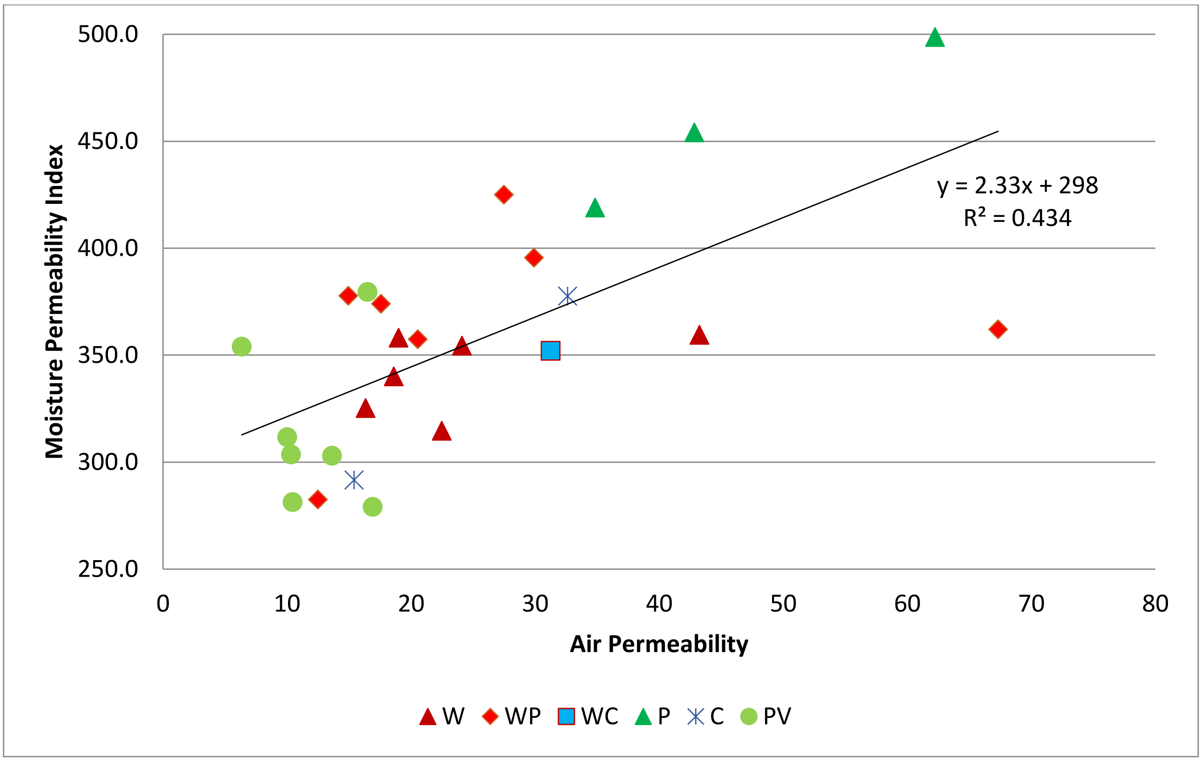


Fig. 17: Moisture Permeability Index *versus* Air-permeability

The analysis and graphical plots of predicted versus actual results indicated that for the same fabric thickness and density, neither fabric weave structure nor fibre type or blend had a significant or consistent effect on thermal resistance (heat insulation), thereby confirming the findings of a number of earlier studies.

Multi-quadratic regression analysis on the water vapour resistance results showed that the latter was mainly dependent upon the fabric mass, with the effects of fabric air-permeability and thickness of borderline significance (**Fig. 18**; Stoffberg). It was also found, that at a constant fabric mass, and possibly, also constant air-permeability and thickness, neither fabric structure (**Fig. 19**; Stoffberg), nor fibre type or blend (**Fig. 20**; Stoffberg), significantly or consistently affected water vapour resistance.

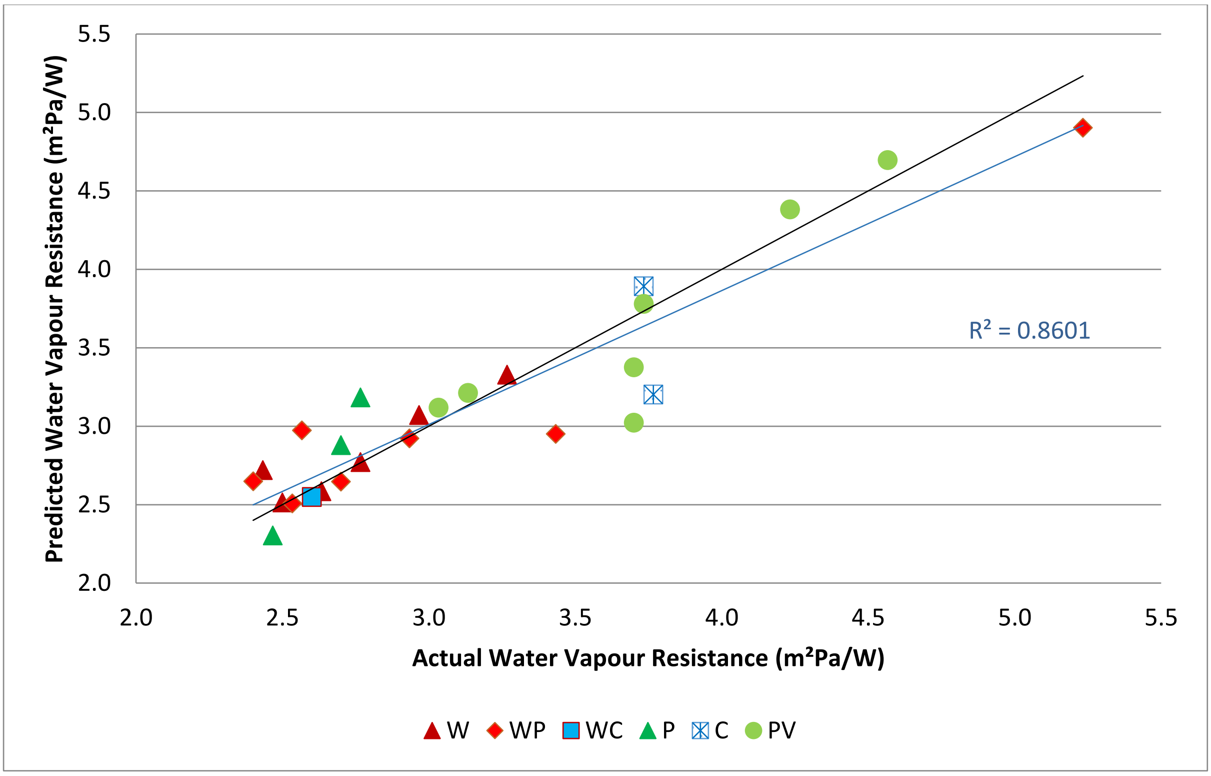


Fig. 18: Predicted *versus* Actual Water Vapour Resistance (Multi-quadratic Regression)

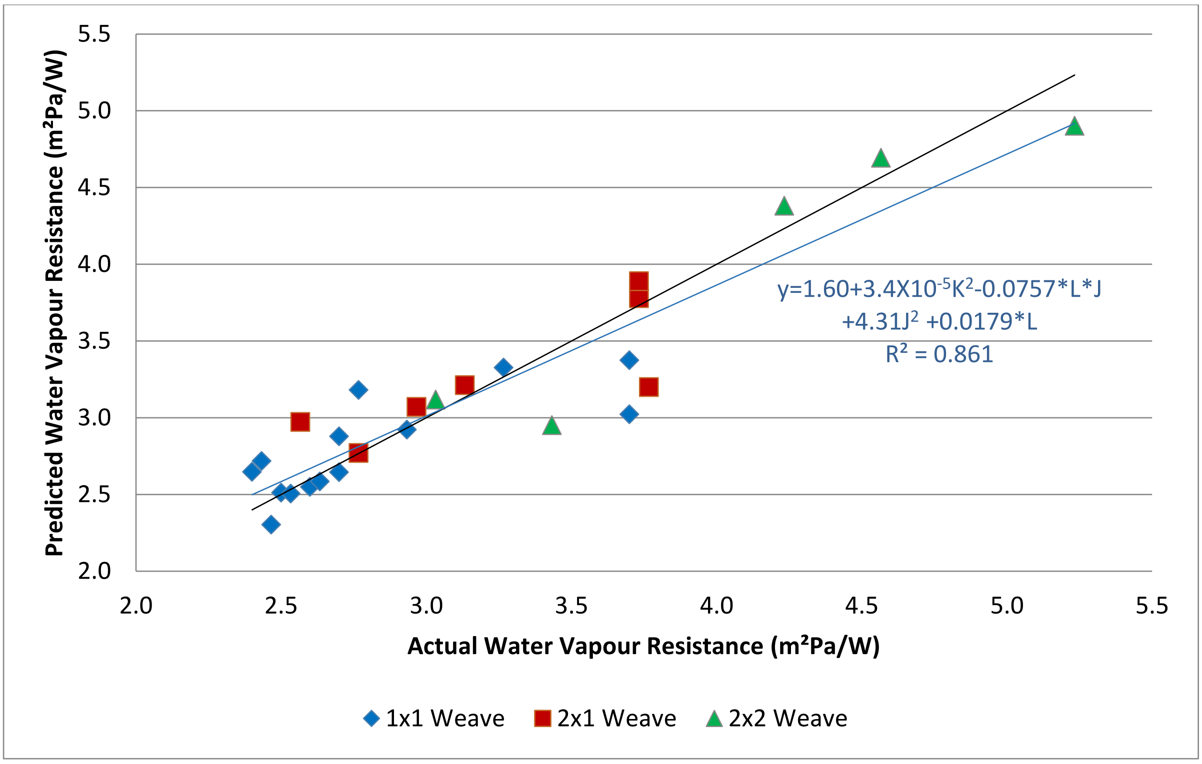


Fig. 19: Predicted *versus* Actual Water Vapour Resistance (Multi-quadratic Regression)

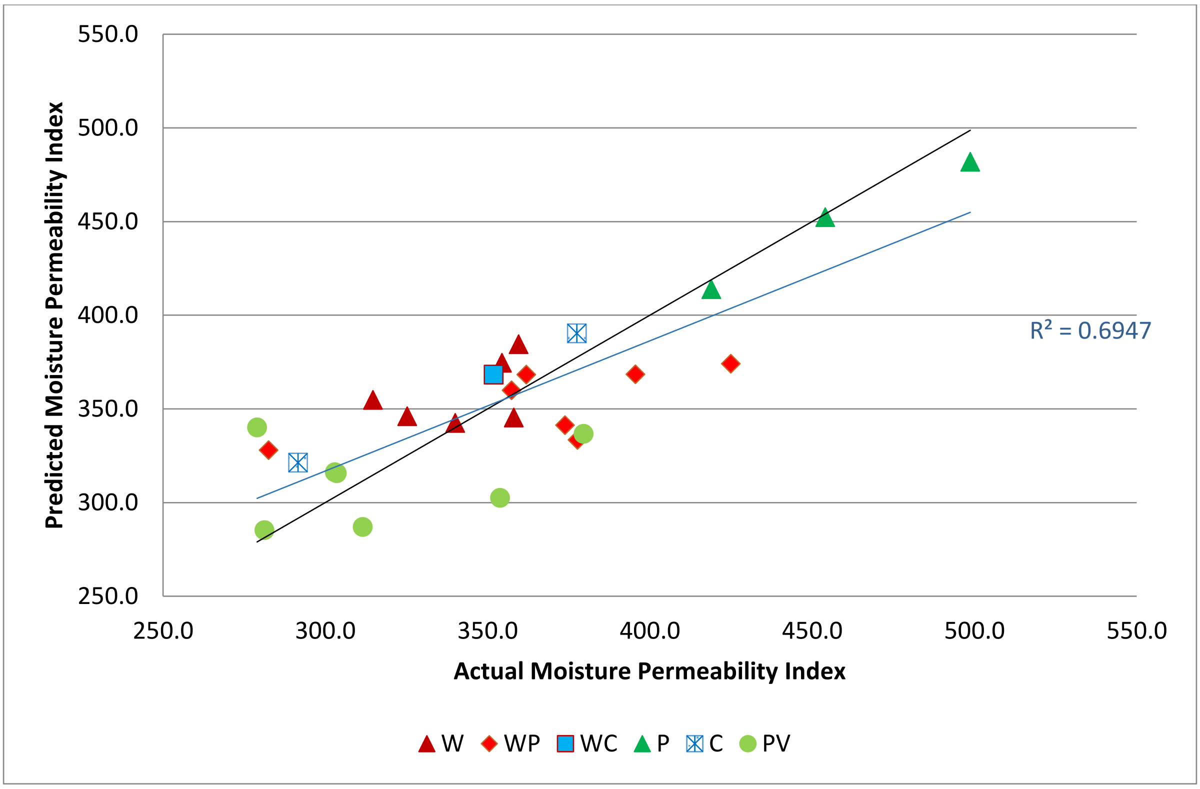


Fig. 20: Predicted *versus* Actual Moisture Permeability Index (Multi-quadratic Regression)

Similar trends were observed for relative water vapour permeability. Similar analyses on the moisture permeability index results indicated that it was mainly affected by fabric air-permeability and thickness (**Fig. 19**; Fig. 49, Stoffberg), it increasing with an increase in fabric air-permeability.

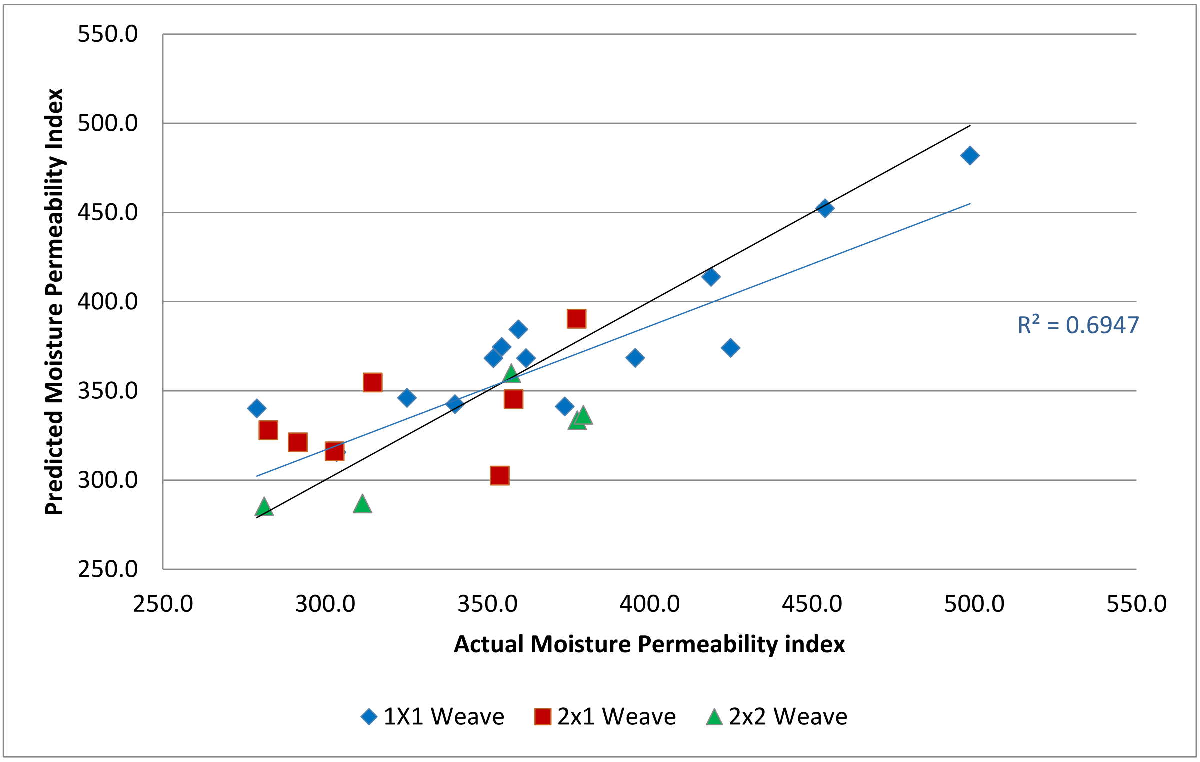


Fig. 21: Predicted *versus* Actual Moisture Permeability Index (Multi-quadratic Regression)

It also appeared that, at a constant air-permeability, thickness and density, neither fabric structure (**Fig. 21**; Stoffberg) nor fibre type or blend (**Fig. 20**; Stoffberg) had a consistent or statistically significant effect on the moisture permeability Index (Figs 20 and 21).

The work of Stoffberg (213) and Stoffberg *et al* (2014?) once again showed that fabric parameters, notably mass, thickness, density and air-permeability, played the major role in the thermal and water vapour resistance of fabric, with neither fibre type or blend nor fabric weave structure, having a consistent or significant effect, confirming the work of a number of previous researchers, such as Mehta (1984) for underwear (**Fig. 22**; Stoffberg). Essentially the question, which the above study posed and answered, was what role, if any, does the fibre type and fabric weave structure play, in the comfort related properties as measured in a laboratory.

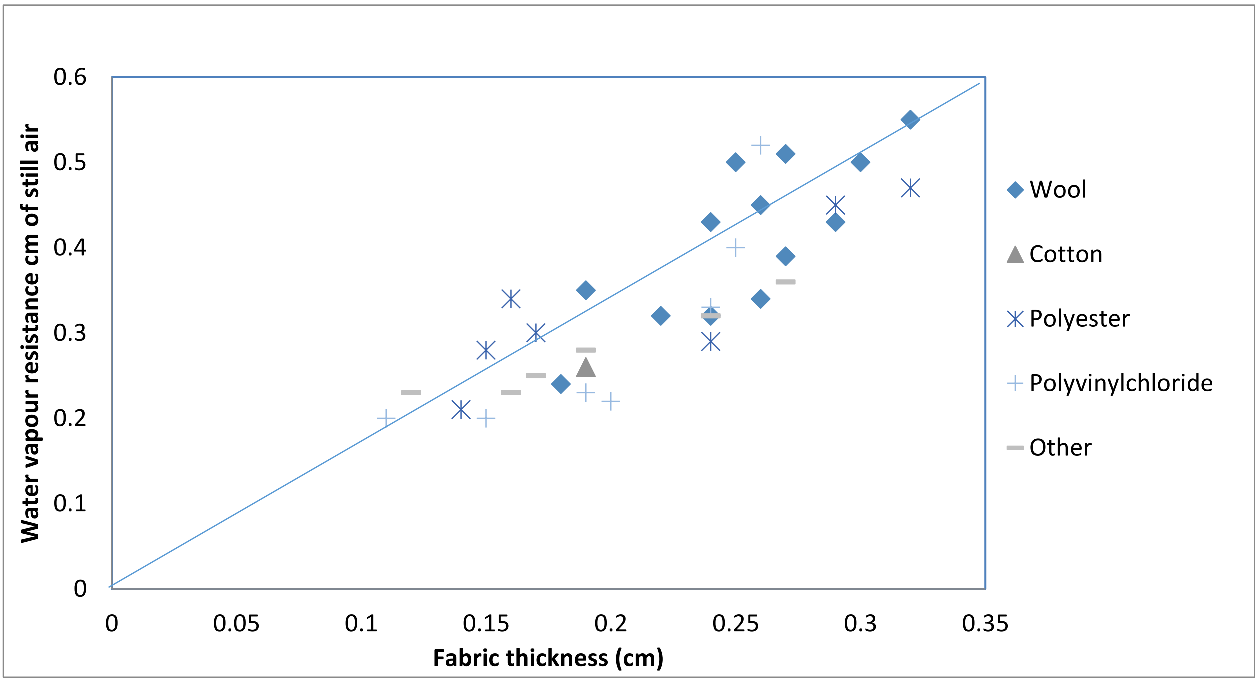


Fig. 22: Dependence of Water Vapour Resistance on Underwear Fabric Thickness

ISO 7730 defines thermal comfort 'as a state of mind that is satisfied by the thermal surroundings' (li, 2001, 55 - Lizaan).

In a follow up study, Britz (2017) investigated the effect of commercial worsted type suiting fabric properties, notably weave, thickness, air-permeability, weight and percentage wool, on the comfort related properties (thermal and moisture resistance) of clothing ensembles, as measured by means of a thermal sweating manikin Walter^{TM}. The study covered 12 identically constructed suits, made from 12 worsted fabrics differing essentially in weave (plain and twill), weight and percentage wool and she used multi-linear and multi-quadratic regression analysis to isolate and quantify the effects of the various fabric parameters (weave, weight and % wool) on the comfort related properties of the suits as measured on Walter^{TM}.

She also used multi-linear and multi-quadratic regression analyses to isolate and quantify the effects of the various already mentioned suiting fabric properties, on the comfort related properties of the ensembles. She found that, although the trends were not always consistent, the thermal resistance (R_t) of the clothing ensemble was mainly affected by the air–permeability of the suiting fabric, and to a lesser extent by the fabric density, R_t increasing as either air-permeability or density decreased, with neither suiting weave structure (i.e. plain or twill weave), nor the wool content appearing to have a consistent, or statistically significant, effect on R_t, once any associated changes in fabric air-permeability and density had been allowed for. This finding indicates that the thermal resistance (heat insulation) of the clothing ensemble (suit, plus shirt and underwear), is mainly affected by the volume of air entrapped within the fabric structure, rather than by the fibre or fibre blend or fabric weave structure, except insofar as the latter three affect the fabric air-permeability and density. This is largely in line with the various fabric test results, where fabric thickness, which relates to volume of air entrapped, came out as the most significant parameter in terms of thermal resistance (i.e. heat insulation).

The water vapour resistance (R_{et}) of the clothing ensemble (i.e. suit, plus shirt and underwear) was, as in the case of the thermal resistance (R_t), mainly affected by the air-permeability of the suiting fabric. In addition to the main effect of air-permeability, suiting fabric thickness and wool content also had a statistically significant effect on R_{et} the three aforementioned variables explaining some 80% of the variation in R_{et}. R_{et} increased with a decrease in suiting fabric air-permeability and with an increase in suiting fabric wool content and/or thickness. It is rather surprising, that water vapour resistance (R_{et}) increased with an increase in the wool content of the suiting fabric.

The water vapour permeability index (I_m), considered by some to provide an overall measure of comfort, was, as in the case of R_t and R_{et}, also mainly affected by the suiting fabric air-permeability, with the effects of fabric thickness, weight (mass) and percentage wool also statistically significant, but far less so, than air-permeability, the trends being largely similar to those for R_{et} and R_t. Certain of the above trends are illustrated in **Figs 23 – 25**. Britz 2017).

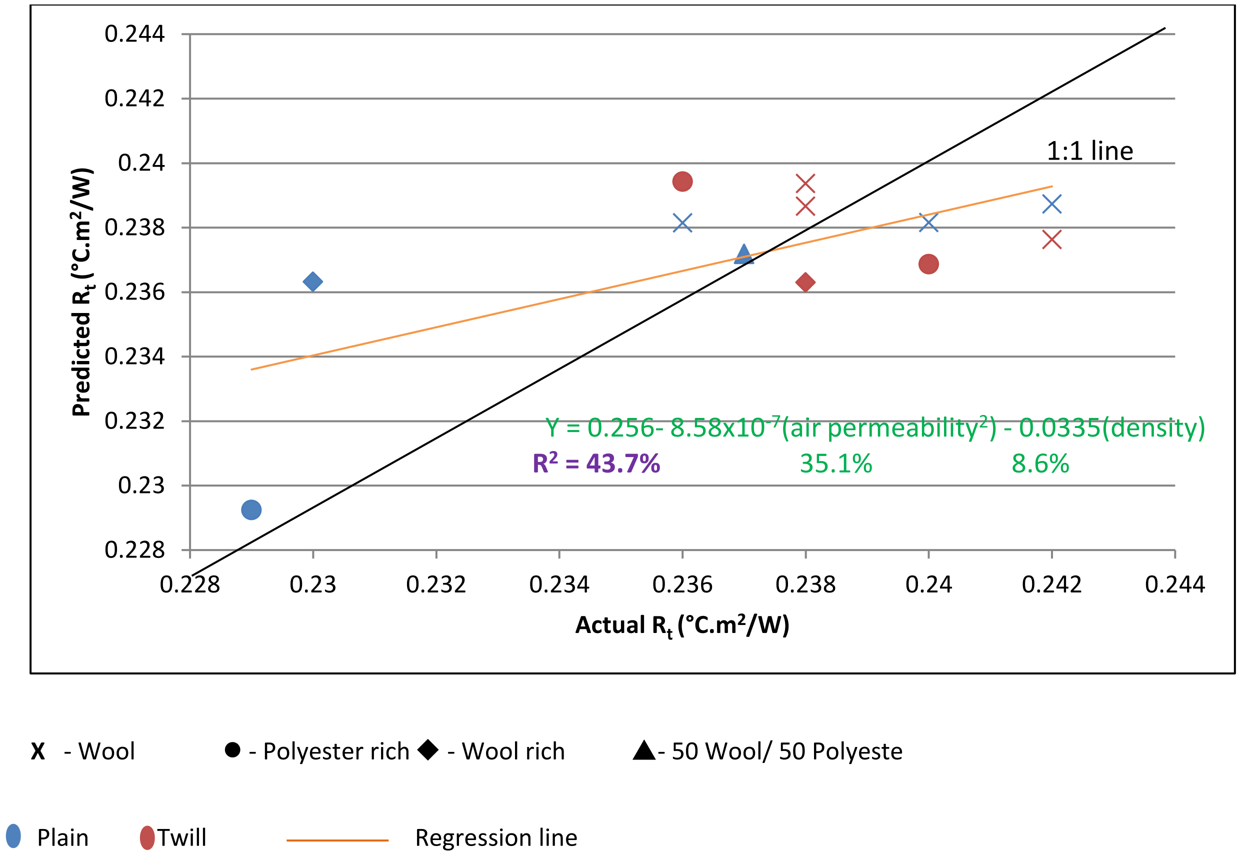


Fig. 23: **Predicted *versus* Actual Clothing Ensemble R_t**

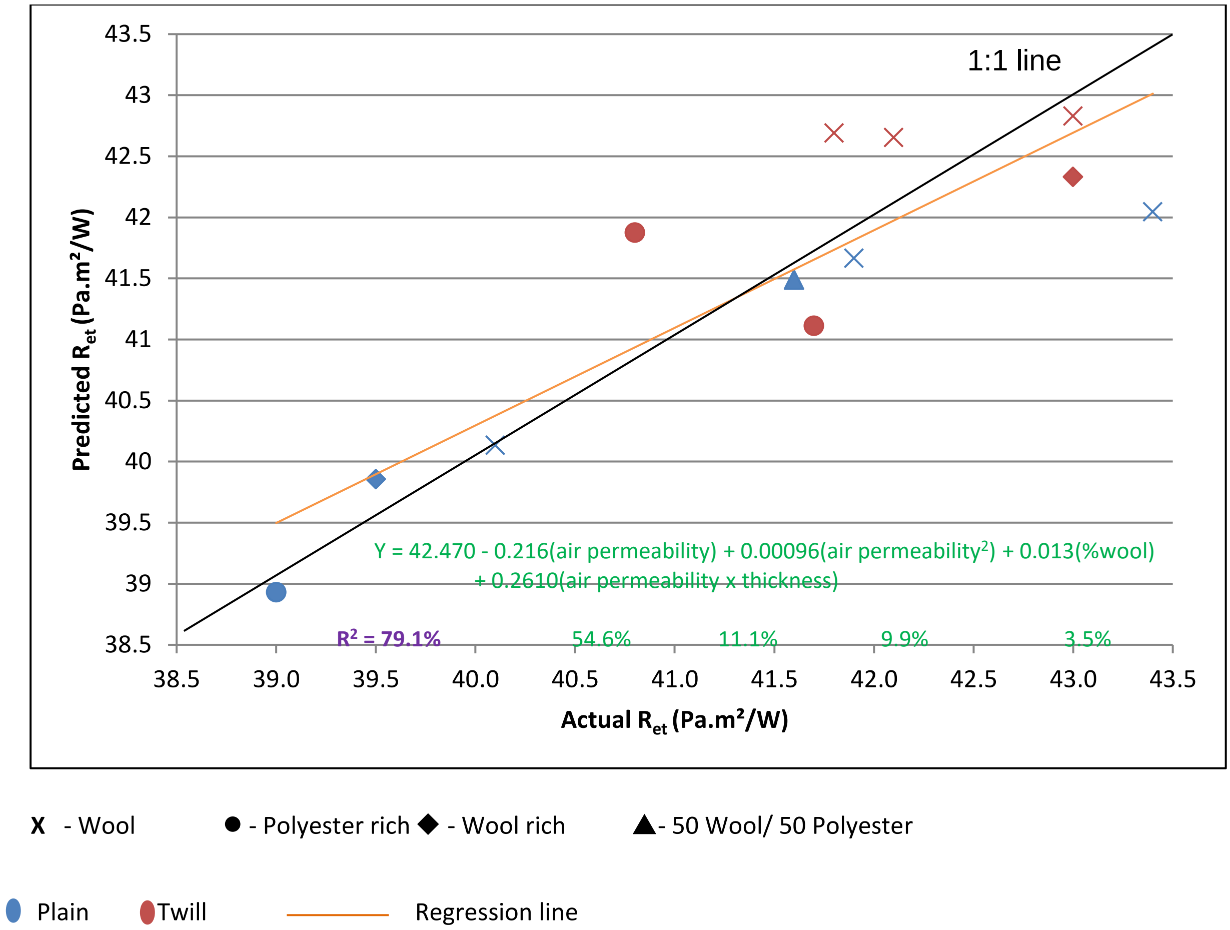


Fig. 24: Predicted *versus* Actual Clothing Ensemble R_{et}

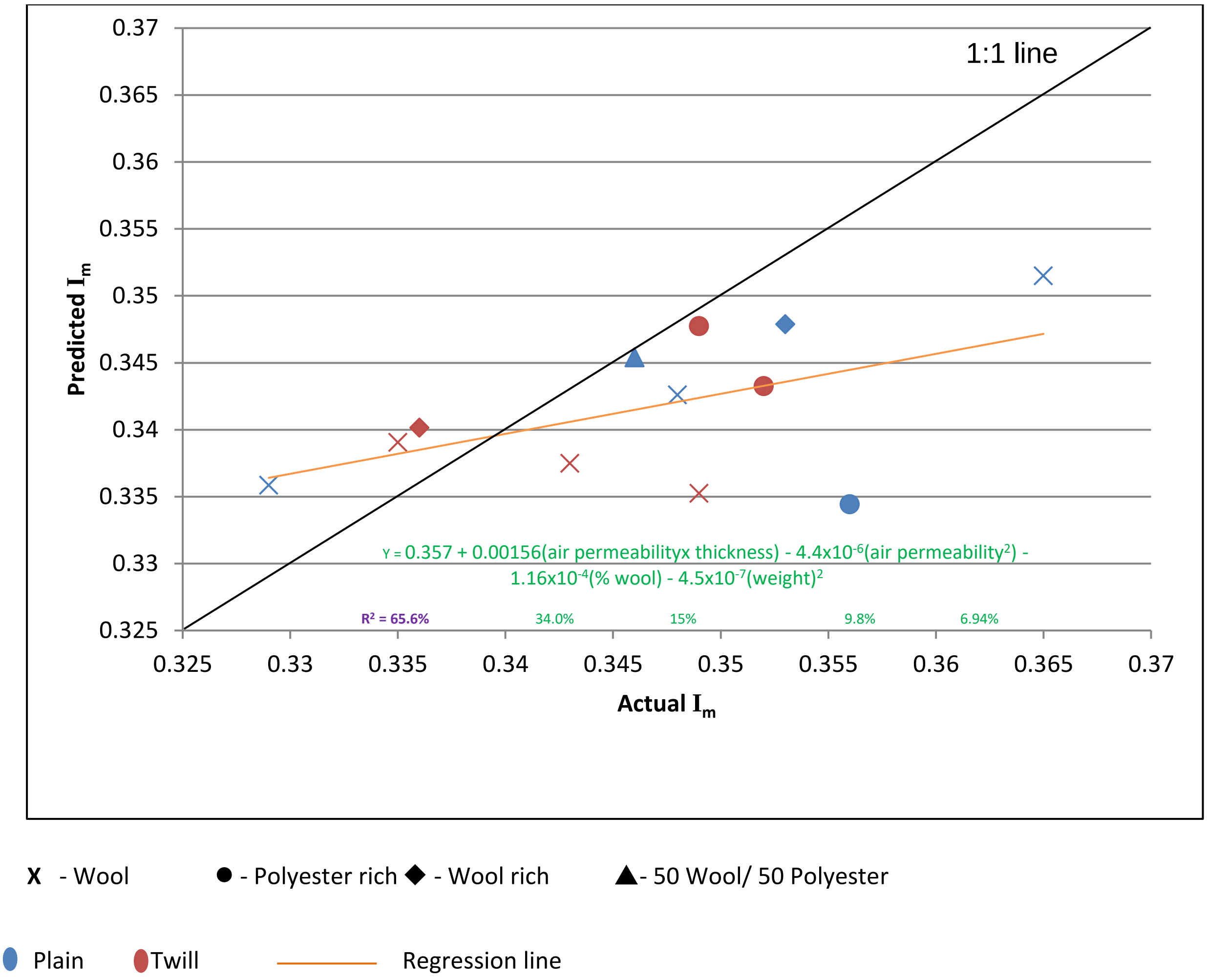
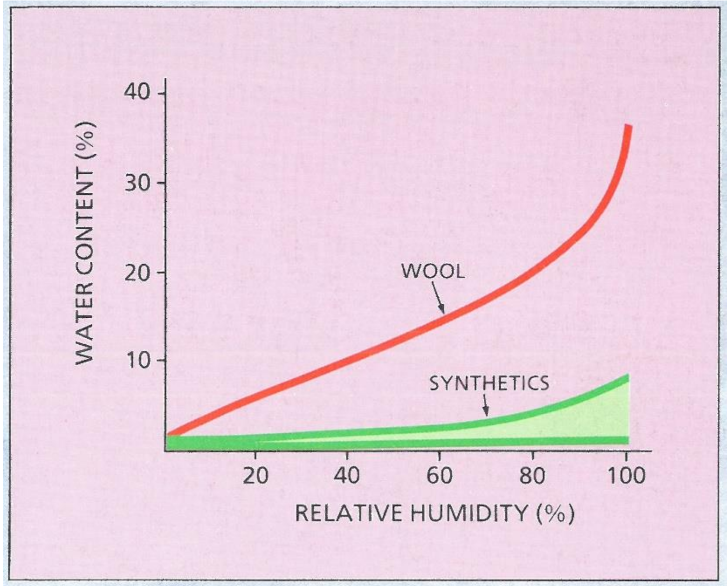


Fig. 25: Predicted *versus* Actual Clothing Ensemble I_m

Therefore, the results of Britz (2017), based upon the comfort-related properties of clothing ensembles (worsted suit, shirt and underwear), as measured on Walter^{TM}, a sweating manikin, followed much the same trends as those obtained previously on a similar set of commercial worsted fabrics, in as much as the fabric structural parameters or properties, such as air-permeability and thickness, rather than fabric weave structure and fibre content and *per sé*, had the most significant effect on the comfort related properties of the clothing ensemble. As could be expected, however, there was not such a strong direct relationship between the clothing ensemble comfort-related properties and the suiting fabric properties, as previously found between the fabric comfort-related and other properties. This is due to the fact that in the clothing ensemble the presence of layers of fabric (underwear, shirt and suit) and, in particular, the associated entrapped air, can be expected to have a relatively large influence on the comfort-related properties of the ensemble, overshadowing the effect of changes in suiting fabric properties, since the suit represents only one component of the ensemble. It therefore appears as if the volume of entrapped air has the main or key, influence on the comfort-related properties of fabrics and clothing as measured instrumentally, in a laboratory, by means, for example, of a sweating guarded hot plate (e.g. Alambeta and Permetest) or sweating manikin (e.g. Walter^{TM}).

Therefore, due to their hydroscopic/hydrophilic nature, natural fibres, both animal (e.g. wool, hair and silk) and plant (e.g. cotton, flax, hemp) generally take up water vapour and perspiration more readily and to a greater extent (degree), than their synthetic counterparts which relates to comfort. Nevertheless, although the wicking properties of the two main types of fibres are more dependent upon the fibre surface characteristics, including the presence of any additive (e.g. lubricants, anti-static, contaminants), than upon the fibre molecular/morphological structure (i.e. fibre substance) which influences the way the fibre responds to liquid moisture, including perspiration, and therefore, ultimately also the fabric and clothing comfort related properties.

When wool and other animal, and even plant, fibres absorb moisture (water vapour) which is then held by molecular forces in their internal structure, they release heat energy, namely the heat of sorption, thereby creating a warming effect. The warming effect can be detected by wearers wearing wool mittens, (Stuart, I.M., Schneider, A.M. and Turner, T.R., Text. Res. J., **59**, pp 324-329, June 1989). Similarly, when they release moisture (e.g. when going from a relatively damp atmosphere to a relatively dry one) they absorb heat energy resulting in a cooling effect. The amount of heat energy released is directly related to the amount of moisture absorbed (**Fig. 26** IWS brochure), wool absorbing as much as 35% of its dry weight in moisture, without feeling wet, this being much more than synthetic fibres (**Fig.26** IWS brochure).



The amount of water vapour absorbed by fibres from the surrounding air depends on humidity. Wool absorbs considerably more than other fibres.

Fig. 26 : Water content vs relative Humidity

On exposure to a saturated atmosphere, the heat produced by one kilogram of dry wool, as it takes up 35% of water vapour, is 960 kilojoules, which is equivalent to about 8 hours heat output by an electric blanket (IWS brochure), the maximum effect being achieved quite quickly, typically within about 2 minutes. When heat of sorption is generated in a wool garment, it produces a 'buffering effect' (i.e. an increased insulation) against the cold (Fig. IWS brochure). A controlled series of trials by the CSIRO involving mittens were carried out using a group of volunteers, in a climate chamber at 7^{o}C and 80%RH. Although the acrylic mittens came closest to resembling wool, it having the greatest heat sorption amongst the synthetic fibres, the subjects all favoured the wool mittens. The temperature rise in dry wool mittens, exposed to a humidity of 80% RH, and a temperature of 5^{o}C, is illustrated in **Fig. 27** (IWS brochure).

In the CSIRO project, sorption heating in simulated winter conditions was studied. This graph shows the temperature rise in dry wool mittens exposed to a humidity of 80% rh at a temperature of 5°C.

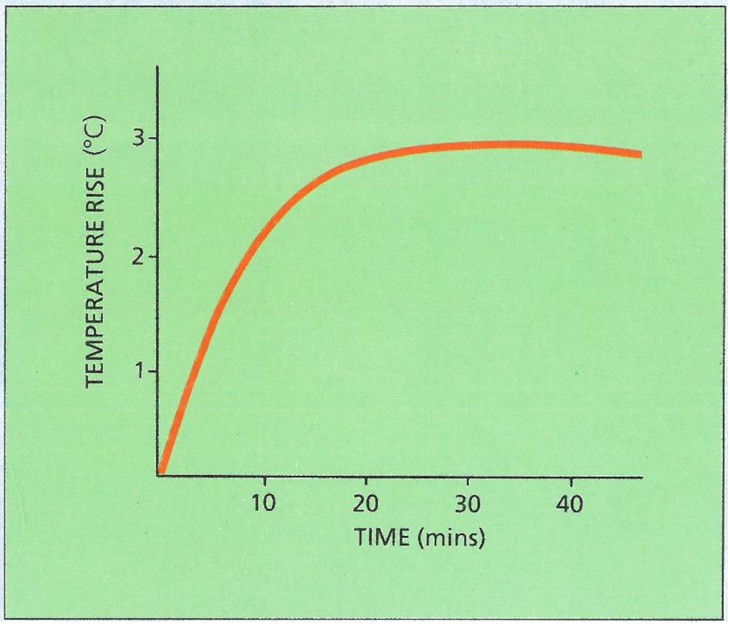
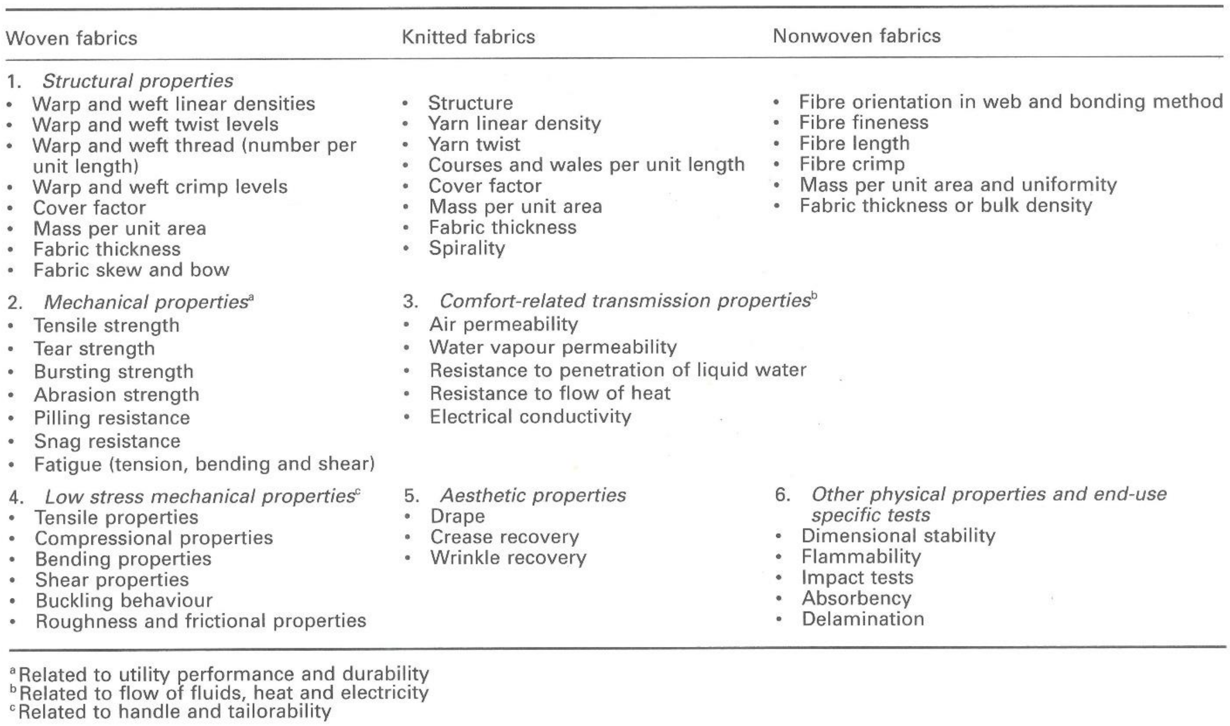


Fig. 27 : Temperature rice in dry wool as Time increases

Kim *et al* (in Fan and Hunter), found a significant effect of fibre type (cotton *versus* polyester), on the vapour pressure and temperature at the fabric surface during dynamic moisture transfer, which are directly related to the sensations of clothing comfort, with the cotton/cotton assembly producing a dryer, warmer feeling at the onset of sweating, than a polyester/polyester mixed assembly, the latter being perceived as cooler but wetter (damper). Wu and Fan showed, both experimentally and theoretically, that a hygroscopic batting in the inner region and a non-hygroscopic batting in the outer region of a clothing assembly are advantageous in terms of thermal comfort, as it reduces condensation within the assembly and the associated dry heat loss.

Fabric performance related properties are highly complex and interrelated, and can broadly be divided into six different groups (**see Table 7**, Kothari Ref. 10 in Fan and Hunter). The relevance and relative importance of the listed properties greatly depend upon the specific application or end-use, making generalisation very risky, if not meaningless.

Table 7 : Fabric performance related properties



Woven fabrics	Knitted fabrics	Nonwoven fabrics
1. *Structural properties*		
• Warp and weft linear densities • Warp and weft twist levels • Warp and weft thread (number per unit length) • Warp and weft crimp levels • Cover factor • Mass per unit area • Fabric thickness • Fabric skew and bow	• Structure • Yarn linear density • Yarn twist • Courses and wales per unit length • Cover factor • Mass per unit area • Fabric thickness • Spirality	• Fibre orientation in web and bonding method • Fibre fineness • Fibre length • Fibre crimp • Mass per unit area and uniformity • Fabric thickness or bulk density
2. *Mechanical properties*[a] • Tensile strength • Tear strength • Bursting strength • Abrasion strength • Pilling resistance • Snag resistance • Fatigue (tension, bending and shear)	3. *Comfort-related transmission properties*[b] • Air permeability • Water vapour permeability • Resistance to penetration of liquid water • Resistance to flow of heat • Electrical conductivity	
4. *Low stress mechanical properties*[c] • Tensile properties • Compressional properties • Bending properties • Shear properties • Buckling behaviour • Roughness and frictional properties	5. *Aesthetic properties* • Drape • Crease recovery • Wrinkle recovery	6. *Other physical properties and end-use specific tests* • Dimensional stability • Flammability • Impact tests • Absorbency • Delamination

[a] Related to utility performance and durability
[b] Related to flow of fluids, heat and electricity
[c] Related to handle and tailorability

Holcombe *et al* (1988 Annual TI World Conference Proceedings p 436, noted) that fabric thermal resistance was largely determined by constructional factors, primarily thickness, rather than by fibre type.

One gram of water takes 2260 joules of heat (energy) from the body in evaporating. The process of water vapour transport from regions of higher, such pressure to regions of lower pressure known as diffusion. It can do so through the pores in a fabric (single diffusion) and/or through the fibre, which acting as a moisture sink or source, the former is the main mechanism, with the diffusion being related to fabric thickness and porosity. Swelling of hydrophilic fibres, due to absorption of water or water vapour, can reduce the porosity of the fabric, and therefore the diffusion of water vapour.

Asuda and Miyama (Yasuda, T. and Miyama M., TRJ, **62**(4), 227-235, 1992) showed that for single layer fabrics (polyester, acrylic, cotton and wool), if the porosity of the fabric is above 66.4%, then all the fabrics have the same water vapour pressure gradient, the characteristic permeability coefficient is nearly identical, regardless of the kind of fibre. Garments with hydrophilic inner layers are useful when moving from normal temperatures to conditions of extreme cold (Li, Y., Zhu, Q. and Yeung, K.W., TRJ, **72**(5), 435-446. 2002).

Layers made of hydrophilic fibres will only exhibit the heat of sorption, warming effect during the transient stage.

Fibres with high radiative sorption constants reduce the percentage of condensation/water coolent within the fibrous batting (Li and Fan, 2006, p201, Song).

Ideally, perspiration should evaporate on the skin itself, utilising the latent heat of evaporation to cool the body. The water vapour so generated needs to be diffused quickly through the clothing, this being the most efficient way of dispersing excess body heat during intense activity, but is dependent upon the surface area of the moisture on the skin available for evaporation. Wool batting next to the skin and polyester batting in the outer region reduces the problem of moisture accumulation within and the total dry heat loss through the clothing layers (Wu and Fan, 2008, 5, in Song page 203).

One of the primary purposes of clothing is to maintain a uniform body temperature under different temperature environmental conditions and to prevent the accumulation of sweat on the skin by allowing perspiration to flow to the outside environment when activity increases.