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Experimental Comfort Evaluation of Baby Diapers in Terms of Liquid Accumulation, Moisture Management and Heat Transfer via Non Destructive Testing

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ABSTRACT

The purpose of this paper is to provide an applied and objective analysis into heat transfer and mass transfer parameters such as relative water vapour permeability, thermal conductivity and thermal absorptivity as well as liquid accumulation of baby diapers which have critical importance on skin health using non-destructive Alambeta and Permetest instruments. SEM investigation was also carried out for characterization of breathable film layer of the diaper assembly. According to the water vapour transmission assessment, it was found that a few hours later, the composite diaper assembly becomes almost zero vapour permeable which results in discomfort and a poor breathability in baby diaper. It was also found that the liquid accumulation in diaper has increased in the course of time. The thickness of the diapers had an important effect on thermal parameters however production type of nonwoven top sheet and back sheet layers had a dramatic effect on these parameters.

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Baby diapers, Thermophysiological comfort, Mass transfer, Heat transfer, Warm-cool feeling, Nonwovens

1. INTRODUCTION

Baby diapers are extensively used for baby care in our day as an indispensable part of daily life. They are one of the most commonly consumed disposable products among adult incontinence pads, sanitary napkins, wet wipes and etc. Baby diapers are especially important in areas such as baby comfort and maintaining dermal skin health. Researchers into this area are mainly focused on issues such as advances in diaper technology, dermal skin health, materials and design, safety and user satisfaction and finally comfort properties.

According to the researchers from institutes of child health, the main advances in diapers' timeline were incorporation of superabsorbent particles into absorbing layer, addition of breathable outer covers and development of acquisition distribution layer [1]. Counts et al. also stated that as a result of continuous innovations, baby diapers are now better fitting, less bulky, eco-friendly, providing prolonged dryness and reduced leakage [2].

Dermal skin health, diaper dermatitis and infection control issues are also important in determining the performance of diapers and development areas. Researchers found that diaper dermatisis, an unwanted skin reaction which caused by diaper use, could be preventable using diapers antifungal and antibacterial agents, improved absorbent tissue structures and composition designs [3-7]. In addition to skin health, some other researchers reported that diaper use also reduces the risk of neonatal infections in babies compared to cloth diapers as well as decreases the risk of eczema [8-10].

Novel diapers having improved design and materials outperform standard diapers in better permeability and odour control via chitosan addition to the fibres mix, better absorption via bamboo fibre blends and antimicrobial

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function via sustainable herbal finishes [11-14]. Traditional diapers, bio-degradable diapers and reusable cloth diapers were compared to each other in a few studies and findings revealed that bio-degradable diapers are the most eco-friendly ones followed by reusable cloth diapers while the first two provided better performance due to reuse and cleaning deteriorates many properties of reusable cloth diapers in extended usage [15-18].

Diapers were also assessed in terms of user satisfaction and safety issues and found to be mostly satisfying by mothers as well as they found to be safe to use by many researchers via extensive testing [19-21]. A number of different issues could also be counted as valuable for the baby diapers, but this paper mostly concentrated on moisture transfer, liquid accumulation and heat transfer issues.

The most comprehensive research for baby diapers was carried out into the comfort evaluation area. Investigators from Kimberly-Clark Corporation compared the comfort perception of breathable and non-breathable baby diapers and found that breathable diapers perform better in improving the health of children' skin, providing a pleasant dry and cool feeling and highly comfortable [22]. The expectations, measurement methods and detailed guidelines for the comfort evaluation were also provided by different institutions in terms of moisture absorption, anti-bacterial effect, breathability, heat transfer and etc. [23-24]. Thermal comfort studies revealed that moisture transfer varied with different diaper types; the breathable film type has the biggest effect on water vapour permeability while top sheet of the diaper was the most important material in determining diaper thermal comfort properties; lastly wetting has increased thermal conductivity and provided a cool feeling [25-27]. Satsumoto and Havenith investigated the local ventilation in baby diapers and found that the ventilation affected by air permeability, construction and design features of the diapers [28]. Yokura and Niwa carried out objective hand measurements for nonwovens used for diapers and reported that the diapers having a high total hand value (THV) of their top sheet nonwovens were estimated to have good hand under both dry and wet conditions as well as the hand could be predicted from the mechanical and surface parameters [29-31]. Non-destructive testing methods were also developed by researchers that could also be used for comfort evaluation of diapers [32-34]. Few more researchers developed novel measurement and assessment techniques of textiles and clothing that could also be useful in designing experiments for baby diapers [35-37].

In this study, in addition to water vapour permeability and thermal transfer parameter measurements, the liquid accumulation rate inside the baby diapers was measured with non-destructive testing as a novel part of the study which is not available within present literature. A new methodology applied in order to assess the liquid accumulation rate instead of liquid absorption measurement.

2. MATERIAL AND METHOD

2.1 Material

Each 5 different baby diapers encoded with 'A', 'B', 'C', 'D', 'E' letters belonging the same company were obtained from a company working in hygiene area and tested for the experimental part. The technical details of diapers were presented in Table 1.

According to the information provided by the diaper producer, breathable film (breathable layer) was made of polyethylene polymer. Top sheets and back sheets were polypropylene based nonwovens (See Table 2 for the production method details). The diapers are also including a superabsorbent nonwoven layer and 2 pieces of thin nonwoven supporting layer.

Table1. Technical details of Baby diapers

Diaper Code	Total thickness (mm)	Total weight (g)	Layer number
A	7,513	29,9	6
B	8,63	30,050	6
C	9,596	34,1	6
D	5,923	15,1	6
E	10,12	42	6

Table 2. Nonwoven Production Methods for Top Sheets and Back Sheets

Diaper Code	Top Sheet	Back sheet	
A	Thermobond	Thermobond	
B	Spunbond	Spunbond	
C	Thermobond	Thermobond	Production Method
D	Spunbond	Spunbond	
E	Airbonded	Airbonded	

2.2 Method

In this study it was investigated that the thermoregulation within the microclimate which is comprised of baby skin and the diaper. To determine breathability, water vapour transmission rate was measured and mass transfer was characterized. In addition to the mass transfer, it was also investigated that the direct heat transfer (heat transfer by conduction) through diaper assembly and it was found that how the diaper is effective on heat change of the skin by time. As different from the available literature, time dependent liquid accumulation caused by body perspiration was also measured. Water vapour transfer, liquid accumulation and heat transfer properties of diapers were investigated using non-destructive test instruments. Non-destructive means there is no specific size of specimen required and no need to cut and/or resize the specimens so all features of the samples are preserved after performing the test. The tests were planned in order to understand transport and accumulation character of the diapers rather than comparing them to each other in basic comfort performance. Thermal comfort and transfer tests were performed under standard laboratory conditions (65% ± 2 relative humidity and 20 ± 2°C) ten times for each. Finally, scanning electron microscope (SEM) image was taken in order to reveal porous structure of the breathable film layer of the diaper assembly. Graphs were prepared for relative water vapour permeability, liquid accumulation, heat transfer and other thermal parameters using OriginPro Program version 9. Statistical analysis was carried out for the results using SPSS 15 statistical software.

2.2.1 Relative water vapour permeability test using Permetest Instrument

Water vapour permeability, in other words 'breathability' was analyzed using Permetest Instrument according to the modified ISO 11092 standard, an instrument measuring in a non-destructive manner.

Relative water vapor permeability (rwvp) calculated according to the Equation (1);

$$r_{wvp} = \frac{q'_{hs}}{q'_{h0}} \cdot 100\% \qquad (1)$$

Here;

- q'h0 is the heat flow when measuring head not covered with a sample
- q'hs is the heat loss in the liquid when measuring head covered with a sample

A portion of the curved and porous surface of the measuring head is optionally continuously or intermittently moistened and subjected to a parallel air flow of adjustable speed within a wind channel. The sample to be tested is placed in the area of high thermal conductivity, which is at a very small distance from the humidified area of about 80 mm in diameter.

The amount of heat evaporated in liquid water and away from the active porous surface is measured by a special integrated system. This ensures that the entire system is successfully measured in a short time and the full signal can be received within a few minutes. The heat flow q'ho that occurs without the sample at the beginning of the measurement is measured. The measuring head is then pulled down and the sample is firmly placed between the head and the wind channel. The display quickly reflects the different temperature effect in the sample, the signal becomes steady and the q'hs value, which represents the amount of heat lost from the moistened measuring head covered with the sample, is read as the new value.

2.2.2 Liquid accumulation test

Liquid accumulation within diapers was assessed using Permetest instrument and a PVC foil. More on this, the diapers were first placed onto measuring head of the Permetest instrument just as a usual water vapour permeability measurement, then the upper side of the diapers were covered with a PVC foil to ensure there is no vapour permeability and accumulation could be enabled for a limited time. In this way, diapers sustained their water vapour permeability on lowermost side while there was no permeability on the uppermost side. The accumulation calculated by subtracting accumulated diaper weight from dry diaper weight.

2.2.3 Heat transfer and thermal parameters test using Alambeta Instrument

Thermal conductivity, thermal resistance and thermal absorptivity values of diapers were tested using Alambeta instrument which is also a non-destructive testing apparatus (Figure 1). As for its configuration and working procedure summarized in a few steps, a special heat power sensing block 4 is attached to a metal block 2 at a constant temperature of 32 ° C higher than the sample temperature (22 ° C). As soon as measurement starts, the measuring head 1 containing the sensing block falls and refers to the measuring sample 5 on the tool base 6 under the measuring head. At this time, the surface temperature of the sample abruptly changes, and the instrument then records the heat power course and solves the transient temperature area on the thin plate exposed to different boundary conditions.

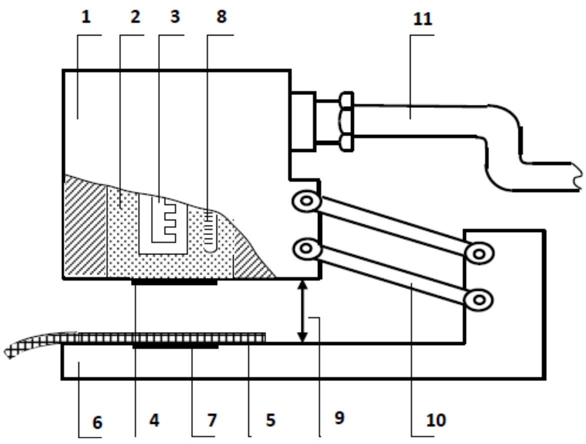

Figure 1. Alambeta non-destructive commercial tester of thermal properties of Textiles [34]

2.2.4 Scanning electron Microscope investigation of breathable film

Breathable film was examined using Scanning Electron Microscope (SEM) (Vega Model, Tescan, Brno, CZECHIA) in order to investigate micro-porous polymeric structure.

3. RESULTS AND DISCUSSION

3.1 Scanning electron Microscope investigation

SEM image was taken in order to reveal porous structure of the breathable film layer of the diaper assembly (Figure 2). It is clear from the figure that breathable film layer is quite porous structure.

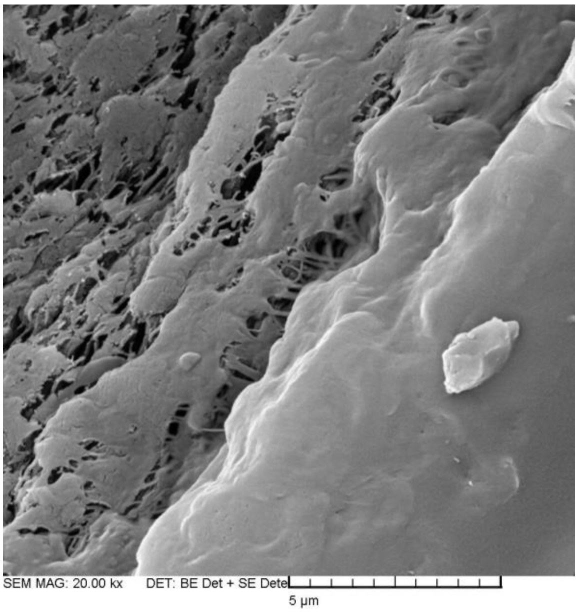

Figure 2. Sem image of breathable film layer

3.2 Liquid accumulation results

Liquid accumulation measurements for diaper samples were carried out as 10 total measurement for each diaper beginning from 0th minute (dry state) to 18th minute (gradually liquid gained) and updated/increased weight of each diaper was recorded at every 2 minutes.

Liquid accumulation results were shown in Figure 3.

According to the Figure 3, the highest liquid accumulation rate was obtained in diaper encoded with ‘C’, followed by ‘A’ and ‘E’ encoded diapers. This is mostly because top sheet and back sheet layers of diaper ‘C’ are thermobond nonwoven reducing the efficiency of the breathable layer and the general diaper structure. Another reason is relative higher weight of the diaper provides more contact area with water vapour and transforming it into liquid form quickly. On the contrary, even though ‘E’ encoded diaper has higher weight and thickness, it showed a moderate increase in liquid accumulation due to air bonded top sheet and back sheet layers provide a more grooved structure boosting moisture transfer upwards and better breathing ability. The diaper A provided a slightly better liquid accumulation performance still very close to diaper ‘C’ as their top sheet and back sheet layers are both thermobond nonwoven. The diaper ‘B’ performed better liquid accumulation performance having Spunbond top sheet and back sheet layers while diaper ‘D’ performed the best liquid accumulation performance due to being the thinnest and lowest weight of all diapers investigated along with its spunbond structure. The variance of analysis was also carried out for liquid accumulation results. According to variance analysis (two-way ANOVA) results, a statistically meaningful difference ($p<0.05$) was found between diaper samples and this shows passing time had a significant effect on liquid accumulation and diapers had different liquid accumulation rates from each other. When standard deviations were compared for each diaper, the most stable diaper was found as diaper ‘D’, while diaper ‘C’ had the highest standard deviation.

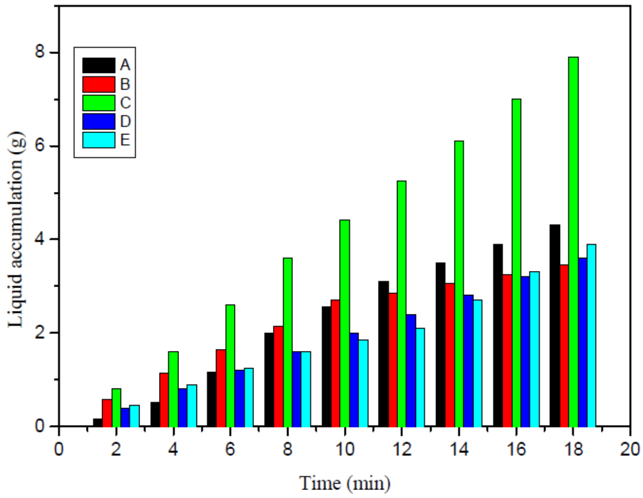

Figure 3. Liquid accumulation results of 5 baby diapers (A-E)

In Figure 4, the mass of the absorbed moisture was expressed as a percentage related to the mass of the particular diaper in 18 minutes. It has revealed that accumulated moisture level is proportional to the mass of the diapers encoded ‘A-D’ except for the diaper ‘E’. Even though diaper ‘E’ has the highest mass, it has performed a lower level of moisture accumulation level relative to its mass. This phenomenon can be attributed to its top sheet layer and back sheet layer made of airbonded nonwoven providing the diaper an open structure and it might allow faster transmission of the liquid while it is in vapour form thus preventing it to be absorbed by super absorbent material inside the diaper. In future studies, a systematic analysis can be carried out to investigate the super absorbent type, content, and moisture management properties in vapour and liquid form within a limited time. The diaper encoded with ‘C’ had the highest moisture accumulation rate relative to its mass as expected and the diaper ‘D’ performed on the contrary. The diapers encoded with ‘A’ and ‘B’ exhibited too close performance relative to their mass.

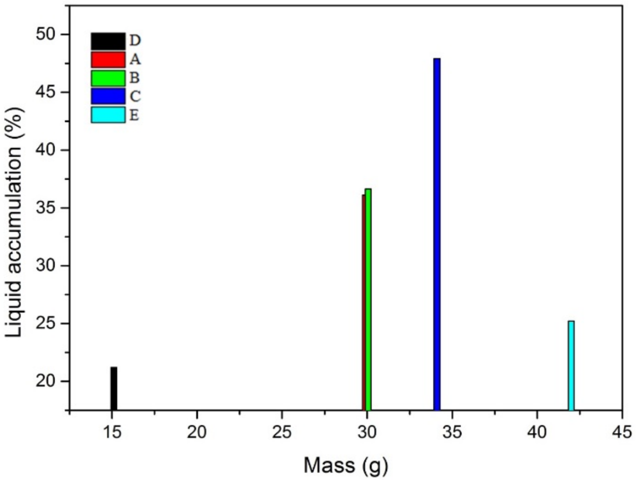

Figure 4. Absorbed moisture/Mass results of 5 baby diapers (A-E)

3.3 Heat transfer and thermal parameters test results

Thermal parameters such as thermal conductivity λ [mW/(m.K)], thermal resistance R [m^2K/W] and thermal absorptivity of diapers were measured using Alambeta instrument in a non-destructive manner. It also measures thickness (h) value which is very relevant to the thermal parameters. Thermal conductivity for textile fabrics represents the function of conducting heat from surface of the fabric to another surface. Thermal resistance, unlike conductivity, is a parameter that minimizes the heat exchange of a textile fabric and provides insulation function. Thermal absorptivity b [$Ws^{1/2}/(m^2K)$] is a new parameter as regards the characterisation of warm-cool feeling of textile fabrics; when it is high, fabrics reveal cool feeling, while it is low, fabrics reveal warm feeling. When multi-layered diaper structure considered, the more moisture kept in the interface fabric after contact, the cooler is its surface, and the higher is the resulting thermal absorptivity. Figure 5 shows thermal parameter test results of all diapers together.

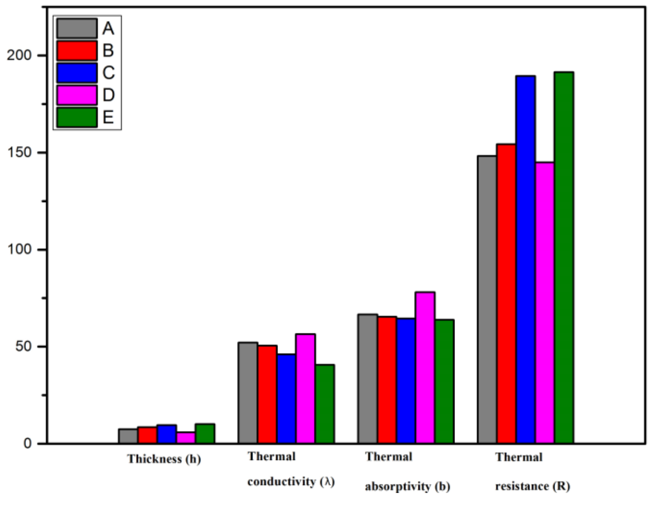

Figure 5. Heat transfer and other thermal parameters test results

According to the Figure 5, thickness of the diapers are close to each other except for the diaper 'D' which is thinner than the rest of the diapers. Thermal conductivity, thermal absorptivity and thermal resistance values were found to be different for all diaper in a relevant manner in between. In fact, the diaper 'E', which is the thickest diaper investigated, had the lowest thermal conductivity and thermal absorptivity values while having the highest thermal resistance value revealing warm feeling as a result. This phenomenon can be attributed to the thickness and production method of its top sheet and backsheet nonwoven layers. The top sheet and back sheet layers of the diaper 'E' are made of airbonded nonwoven. Airbonded nonwovens exhibit a bulky and open structure. Therefore, this bulky and open structure provides additional thermal resistance making the diaper 'E' with the lowest thermal conductivity. On the contrary, the diaper 'D', which is the thinnest diaper investigated, had the highest thermal conductivity and thermal absorptivity values while having the lowest thermal resistance value revealing cool feeling as a result. This phenomenon can also be attributed to the thickness and production method of its top sheet and backsheet nonwoven layers. The top sheet and back sheet layers of the diaper 'D' are made of spunbonded nonwoven. Spunbonded nonwovens exhibit a thinner structure in comparison with the other thermal web bonding methods. Therefore, this thin structure lowers the thermal resistance and increases thermal conductivity within the diaper. The rest of the diapers provided likewise results in that thermal conductivity and thermal absorptivity values have decreased while thermal resistance value has increased with increasing thickness and revealed same behavior on the contrary. The diaper 'D' had the highest thermal absorptivity which can be explained by its thinner structure. The wearer of this diaper will have a cool feeling due to its higher thermal absorptivity. This can be an advantage under steady-state conditions, however, it might provide a super-cooling effect under wet conditions in lower temperatures and the wearer will feel discomfort at the end. Similarly, the diaper 'E' had the lowest thermal absorptivity which can be explained by its thinner structure. The wearer of this diaper will have a warm feeling due to its lower thermal absorptivity. This can be achieved under steady-state conditions, however, it might provide a cooler feeling effect under wet conditions in lower temperatures to some extent. To assess all heat transfer and thermal parameters test results together, the findings were found to be compliant with relevant literature. In fact, diapers with the lower thickness performed higher thermal conductivity and lower thermal resistance values. The thicker diapers exhibited higher thermal absorptivity values providing a cool feeling for the wearer and thinner diapers performed adversely. Therefore, the thickness can be accepted as the most effective and determinant parameter of all parameters examined. The relationships between thermal parameters are statistically determined using the distance function of the correlation method. Here, the distance of the variables to each other decreases the rate of affecting each other, and vice versa, this ratio increases. This method produces a proximity matrix of values. According to this analysis, thermal conductivity was affected by the thickness at most with a proximity value of -,951 followed by thermal resistance with a proximity value of -,925 and thermal absorptivity with a proximity value of ,787. It means that thermal conductivity remarkably decreases by increasing thickness and thermal resistance respectively. On the other hand, the thermal conductivity increases with increasing thermal absorptivity as they have a positive relation. Another parameter, thermal absorptivity, was affected by the thickness at most with a proximity value of -,897 followed by thermal conductivity with a proximity value of ,787, and thermal resistance with a proximity value of -,640. It means that thermal absorptivity remarkably decreases by increasing thickness and thermal resistance respectively; however, it increases with increasing thermal conductivity positively. Lastly, thermal resistance was affected by the thermal conductivity at most with a proximity value of -,925 followed by thickness with a proximity value of ,889 and thermal absorptivity with a proximity value of -,640. It means that thermal resistance remarkably decreases by increasing thermal conductivity and thermal absorptivity respectively; however, it increases considerably with increasing thickness value as they have a positive relation. These statistical evaluations have supported the findings of heat transfer and thermal parameters test results and their interpretations presented here.

3.4 Relative water vapour permeability results

Diaper 'B' were chosen for relative water vapour permeability test as a reference diaper due to its moderate behaviour performed in liquid accumulation and thermal parameters tests in order to determine breathing character of the diaper assembly. Relative water vapour permeability tests were carried out for 3 hours by recording permeability values every 2 minutes and 90 measurements were performed in total. According to the water vapour transmission assessment graph (Figure 6), it was found that a few hours later, the composite diaper assembly becomes almost zero vapour permeable which results in discomfort and a poor breathability in baby diaper. In Figure 6, the unit on the vertical axis can be also understood as relative cooling flow or accumulated moisture. This figure expresses the moisture accumulation in the tested diaper that after some time, when the condensed water vapour fulfils the volume of the diaper, the moisture flow stops and the pores are blocked.

4. CONCLUSION

It was found that the thickness and mass of the diaper assembly was an important factor in determining the liquid accumulation rates of diaper assemblies as liquid accumulation proportionally increased with increasing mass of the particular diaper in general, however, types of the top sheet and back sheet layers had also a remarkable effect such that the diaper having the highest thickness and mass performed a moderate increase in liquid accumulation due to air bonded top sheet and back sheet layers providing an open and more comfortable structure.

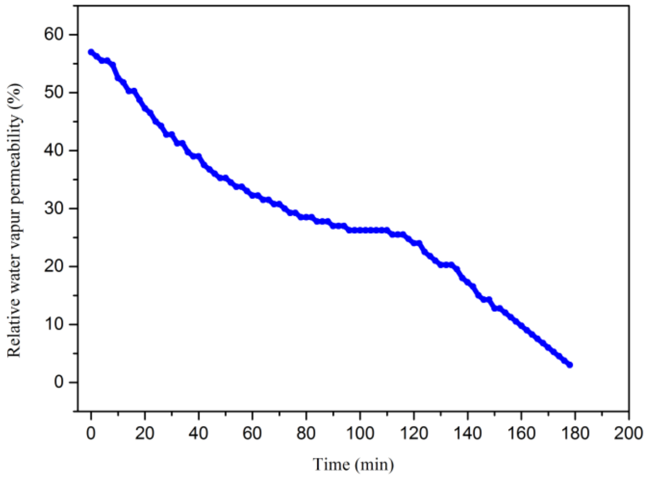

Figure 6. Relative water vapour permeability result of diaper 'B'

The thickness had a dramatic effect on thermal conductivity and thermal resistance of all diapers investigated; the diaper 'E', which is the thickest diaper investigated, had the lowest thermal conductivity while having the highest thermal resistance value revealing warm feeling. Contrarily, the diaper 'D', which is the thinnest diaper investigated showed the highest thermal conductivity while having the lowest thermal resistance value revealing a cool feeling due to its highest thermal absorptivity value.

Time-dependent relative water vapour permeability assessment revealed that after some time, when the condensed water vapour fulfills the volume of the diaper, the moisture flow stops. As accumulated liquid blocks the pores, the diaper becomes almost zero water vapour permeable.

Finally, the SEM image revealed that breathable film layer has quite porous structure. The heat transfer, mass transfer and accumulation assessment findings of this study provide a promising understanding into overall baby diaper comfort that could be beneficial for diaper developers, baby caring people and healthcare professionals.

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