Research progress on the evaluation of thermal and moisture comfort of disposable diapers for babies

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Abstract. In order to further improve evaluation of baby disposable diapers and optimize product design, as well as enhance thermal and moisture comfort and safety of the baby, heat and moisture transfer mechanisms in the wearing state of diapers were analysed, and current evaluation technologies of diaper’s thermal and moisture comfort were summarized from material and product perspectives. In view of current problems, the following suggestions were proposed for improvement: 1) It is necessary to pay attention to the effects of changes after urine absorption in properties of diaper materials and the dynamic changes in size of the micro-space underneath the diaper on thermal and moisture comfort; 2) Experiments for evaluation need to be closer to life scene and the manikin system needs to be standardized; 3) In order to predict skin health of babies in the future research, correlation between thermal and moisture comfort and skin damage needs to be established.

1. Introduction
Baby disposable diapers composed of multi-layer nonwoven materials are often regarded as a liquid absorption and control system [1, 2]. Therefore, good moisture management capacity is a prerequisite for their normal use to prevent urine leakage and keep baby skin dry [3]. In nearly 70 years of diaper development history, scholars and R&D experts have been committed to optimization and innovation of diaper materials, e.g. adding SAP (Super Absorbent Polymer) in the core layer has greatly enhanced incontinence protective performance of diapers [4, 5]. Nevertheless, excellent moisture management capacity of diapers can reduce the overall heat and moisture transfer performance, thus causing baby’s physiological thermogenesis, heat released from perspiration and urine/feces, and water vapor generated by evaporation unable to transfer to the external environment timely and effectively. Even diaper materials swell after urine absorption and compress the micro-space between the diaper and baby skin, causing temperature and humidity of the microclimate to rise, which will lead to baby’s thermal and wet discomfort, heat load, diaper rash and other health threats and diseases. In recent years, scholars began to pay attention to thermal and moisture comfort of diapers and applied new technology for optimization, e.g. breathable diapers with a microporous membrane on the back layer [6, 7], which are permeable to air and vapor, but impervious to liquid, providing a dry and comfort microclimate for babies.

Thermal and moisture comfort evaluation of baby disposable diapers is an important stage before mass production, and closely related to safety and comfort of the finished product. In current research for evaluation of diaper materials, compared with heat and moisture transfer performance, evaluation
methods and standards for moisture management capacity are more systematic. And in fact, there was no relevant evaluation standards for heat and moisture transfer performance of diaper materials, most researchers conducted small-scale bench-top tests on diaper multi-layer materials after making some improvements on testing devices or methods for conventional fabrics. Although researchers have made a lot of efforts to improve equipment, develop new indicators, make these tests closer to real life, and have obtained some valuable results, these material test results cannot represent the overall performance of diapers. Therefore, to measure and evaluate thermal and moisture comfort in the wearing state of diapers has become a trend and hotspot in related research fields.

At present, a kind of thermal manikin simulating the size and temperature of a real baby becomes the main equipment of diaper wear trials. Some researchers have developed partial or full-scale baby manikins to measure and analyze surface temperature and microclimate parameters (e.g. temperature and humidity, water vapor pressure, ventilation, etc.) in the wearing state of diapers [1, 8, 9]. However, due to a lack of evaluation standards and methods for baby manikins and diapers, these scholars set up manikin parameters, postures and control modes with large differences according to their respective research purposes. Meanwhile, they did not consider the factors influencing thermal and moisture comfort comprehensively. Therefore, based on specific functional orientation of baby disposable diapers, this paper reviewed current research progress in the evaluation field of diapers’ thermal and moisture comfort by analyzing heat and moisture mechanism in their wearing state, summarized and analyzed the problems and deficiencies in these studies. Furthermore, possible ways were proposed for improvement of thermal and moisture comfort evaluation research for baby disposable diapers in the near future.

2. Heat and moisture transfer mechanism in diapers

The difference between diapers and other types of clothing is that diapers have two basic functions of absorbing and storing urine but clothing cannot. Consequently, besides serving as a heat and moisture transfer medium between the wearer and the external environment, it can also manage liquid moisture transfer, absorption and storage. Meanwhile, as the amount of urine absorption increases, the wearer’s thermal and moisture comfort provided by the diaper is also changing, so heat and moisture transfer mechanism in the diaper must be analyzed in a dynamic process.

Figure 1 shows the difference of heat and moisture transfer process in diapers before and after urination. As illustrated in Figure 1(a), the liquid moisture management capacity has not yet worked in the dry state before urination. In that case, heat and moisture generated by the wearer will be released to the external environment through multi-layer nonwoven materials of diaper. However, heat and moisture transfer process through diaper materials is much slower than conventional fabrics. This is mainly because thick multi-layer structure of diapers and the plastic water-proof film on the backsheet have great resistance to air and water vapor transmission, and inevitably resulting in poor air and moisture permeability. Therefore, we should find ways to improve thermal and moisture comfort of diapers by reducing the mugginess and dampness feel in their dry state. After urination as shown in Figure 1(b), SAP particles in the absorbent core contain hydrophilic groups, and when these particles encounter water molecules, the two will form various hydration states together. The water-containing absorbent core will increase the thermal conductivity of diapers [10, 11], thus accelerating heat exchange between human body and the environment. However, the volume of SAP articles will increase sharply after urine absorption, and lead to collision and friction between each other. This collision and friction will cause some water molecules to break away from hydration groups, and they will become free water molecules. Ultimately, due to low permeability of the backsheet, these free water molecules and other free ones generated from urine evaporation, will be released into the microspace between human skin and diaper, thereby increasing humidity of the microclimate closest to the skin and then causing human discomfort. It can be seen that improving the microclimate underneath the diaper after urination is a significant approach for thermal and moisture comfort optimization.
3. Evaluation of thermal and moisture comfort of diaper materials

Excellent moisture management capacity of diaper materials usually ensures their basic function, that is, super water absorption and retention capacity. However, this capacity often restricts heat and moisture transfer performance and interacts with it, and then both have an influence on the thermal and moisture comfort of diapers. Therefore, evaluation of diaper materials includes two kinds of tests, one is for liquid moisture management capacity, the other is for heat and moisture transfer performance.

3.1. Liquid moisture management capacity test

Currently, there are relevant test standards and methods at home and abroad for liquid moisture management capacity of single-layer or multi-layer diaper materials to evaluate five sub-performances including liquid absorption, liquid retention, liquid conduction, leakage prevention and wetback prevention. It should be noted that each layer has a clear functional orientation, e.g. liquid absorption and retention are mainly provided by SAP particles in the absorbent core; liquid conduction is mainly provided by topsheet and acquisition layer; wetback prevention performance is mainly provided by topsheet; leakage prevention performance is mainly contributed by backsheet. Therefore, corresponding indicators and testing methods are specified for SAP particles and other independent layers in these standards.

Each layer plays a different role as urine absorption process goes by, as shown in Figure 2. However, since a diaper is made of multi-layer nonwoven materials bonded together by hot melt adhesives [12], the five sub-performances depend on the interaction and cooperation of these layers. Compared with single-layer test, multi-layer test is more accordance with the actual case, thus the...
results are more accurate. In summary, some problems and corresponding suggestions for current evaluation standards are proposed as follows.

1) **It is suggested that experimental devices be designed to meet actual situations.** For example, we can see a large difference in pressure device design and pressure parameter settings among different standards when simulating the pressed state of diaper materials, as shown in Table 1. However, they are lack of unity and descriptions of application scope. Therefore, it is recommended that the pressure device and relevant parameters should be uniformly designed and set according to actual pressure situation of diaper materials in the life scene.

| Table 1. Simulation of disposable diaper materials under pressure in current testing standards. |
|-----------------------------------------------|
| **Testing standards** | **Objects** | **Indicators** | **Pressure device** | **Pressure parameters** |
|-----------------------|-------------|----------------|--------------------|------------------------|
| GB/T 22875-2018       | SAP particles | absorption against pressure | piston and cylinder apparatus | 2.068 kPa 60 |
| ISO 17190-6:2001      | SAP particles | liquid retention capacity | centrifuge relative centrifugal force 250 g | 3 |
| GB/T 28004-2011       | multi-layer material | rewet/leakage standard pressure block | 1.500 kPa 1 |
| GB/T 24218.14-2010    | topsheet | wetback simulated baby weight | 3.920 kPa 2 |

2) **It is required to pay attention to the changing characteristics of material liquid moisture management capacity.** Information can be drawn from liquid conduction test of topsheet that the rate of liquid conduction will change as frequency of urination increases. Therefore, two indicators are required including liquid strike-through time and repeated liquid strike-through time for the test. Similarly, other sub-performances will be different as frequency of urination increases. In this paper, it is recommended to add test indicators for multiple urinations, to observe performances of diaper when absorbing two times or more. Actually, some researchers used MMT (Moisture Management Tester) and proposed a comprehensive indicator $MAC$, which can characterize moisture accumulating capacity of the overall diaper materials [13], according to the liquid content dynamic change with testing time. It is an attempt and innovation in the development of comprehensive evaluation indicators for liquid moisture management capacity.

3) **It is necessary to consider the influences of environmental factors.** Test environment parameters specified in the standard are temperature $23 \pm 2 ^\circ C$ and relative humidity $50 \pm 5 \%$, and the standard deviation between different standards may be different. Therefore, the test results only reflect performances of diaper materials under specific environmental conditions, and influences of environmental factors are not considered yet.

Since liquid moisture management capacity of diaper materials only has influence on wet comfort, it cannot actually represent the comprehensive thermal and moisture comfort. Comparatively speaking, heat and moisture transfer performance that directly influences wearer’s thermal and wet comfort is more important.

### 3.2. Heat and moisture transfer performance test

Thermal and evaporative resistance testing methods of the overall diaper materials are similar to those of thick conventional fabrics. Both can be represented by fixed temperature gradient between upper and lower heat sources of fabric/material or fixed vapor pressure gradient between inner and outer surfaces of fabric/material respectively divided by heat or water vapor flow per unit area through fabric/material. But for diaper materials, the performances under wet conditions becomes important test items due to their unique liquid absorption function. In order to obtain performances of diaper multi-layer materials under dry and wet conditions, researchers from Japan [10, 11], Turkey [14, 15]
and China [1, 16] used conventional equipment like KES-F7 Thermo Labo II or Alambeta contact cold-hot feeling testers, YG461E digital air permeability meter as well as general methods like Cup method to obtain heat transfer performance (indicators including thermal conductivity, thermal resistance and heat absorption), moisture transfer performance (indicators including evaporative resistance, water-vapor transmission rate, and desorption drying rate), and air permeability. It is noted that due to non-uniform distribution of SAP particles and fluff pulp in the absorbent core of diapers, it is difficult to obtain accurate and effective measurement results in the water-vapor transmission rate test under wet conditions.

Additionally, diaper materials swell after they absorb urine [17]. After absorption, the volume expansion and weight increase of the material may cause the contact pressure and space state to change between diaper materials and skin representing heat and water vapor source. Therefore, it is necessary to set proper pressure value when diaper materials contact with baby skin, and simulate size and range of the space between them. Fortunately, based on KES-F7 system, Chinese researchers made some attempts to simulate four contact situations between diaper and skin, which included direct and spatial contact under both dry and wet conditions, to measure heat preservation rate of the overall diaper materials [18], as shown in Figure 3. However, this research did not clearly describe how to construct a space and how to quantify, and only created wet conditions by simulating baby’s sweating state instead of urinating.

Figure 3. Four contact situations between diaper sample and heat source board (simulated skin).

Besides, in medical protective clothing research area, some scholars used infrared thermographer to monitor temperature changes of non-woven fabric outer surface under dry and wet conditions, and proposed a new index named fabric surface temperature changing rate to characterize its dynamic heat transfer properties [19]. Although thermal and moisture wearing comfort is mainly related to the temperature changes of fabric inner surface, this non-contact measurements undoubtedly provides inspirations for evaluation of diaper’s heat and moisture transfer performance.

4. Evaluation of thermal and moisture comfort of diaper products

In diaper material test, most materials are flat samples after cutting off elastic materials placed around the waist and legs. However, when a baby is wearing a diaper, his/her thermal and moisture comfort is influenced not only by thermal and moisture properties of diaper materials, but also by other factors such as diaper type and structure, baby activities, and environmental conditions, which cannot be obtained by material testing methods. Therefore, evaluation of diaper products in their wearing state and without damage (e.g. cutting) is an indispensable part of the entire research on thermal and moisture comfort of baby diapers. Currently, two evaluation methods for diaper products include baby clinical trial and manikin wear trial.

4.1. Baby clinical trial

As early as baby disposable diaper was invented, scholars and R&D experts were keen to conduct real baby clinical trials to collect physiological data of baby buttock skin (e.g. transepidermal water loss, moisture content and pH value), skin assessment scores and user experience from baby caregivers (mother, nurse or doctor), as shown in Table 2.
### Table 2. Information from baby clinical trials.

| Researcher | Influencing factor       | Study duration (weeks) | Number of babies | Data record | Indicator                  |
|------------|--------------------------|------------------------|------------------|-------------|---------------------------|
| Jordan[20] | • diaper type            | 5                      | 1089             | diaper rash grading scale | skin assessment score |
|            | • changing frequency     |                        |                  |             |                           |
| Campbell[21]| • diaper type           | 16                     | 1614             | diaper rash grading scale | skin assessment score |
|            |                          |                        |                  |             | evaporimeter              |
|            |                          |                        |                  |             | transepidermal water loss |
| Davis[22]  | • diaper type            | 15                     | 150              | diaper rash grading scale | skin assessment score |
|            |                          |                        |                  |             | evaporimeter              |
|            |                          |                        |                  |             | transepidermal water loss |
|            |                          |                        |                  |             | pH electrode              |
|            |                          |                        |                  |             | skin pH                   |
|            |                          |                        |                  |             | pH electrode              |
|            |                          |                        |                  |             | skin pH                   |
|            |                          |                        |                  |             | IBS meter                 |
|            |                          |                        |                  |             | electrical conductance    |
|            |                          |                        |                  |             | (moisture content)        |
| Berg[23]   | • cover or not           | 16                     | 1601             | diaper rash grading scale | skin assessment score |
| Akin[6]    | • breathable or not      | 7                      | 230-260          | diaper rash grading scale | skin assessment score |
| Wang[24]   | • topsheet structure     | 4                      | unknown          | diaper rash grading scale | skin assessment score |
| Yuan[25]   | • material               | 4                      | 80               | diaper rash grading scale | skin assessment score |

Although the results obtained by baby clinical trials is derived from human body reactions, this type of trials also have the following shortcomings.

1) **The experiment protocol is very complicated.** Generally, long intervals existed between different stages of the experiment, causing a longer study duration which lasts four weeks at least. Besides, there was a huge number of baby subjects, which is not easy to control under experimental conditions.

2) **The collected data are not accurate.** Because the work of subjective and objective data collection was done on baby’s bared skin after diaper was taken off, these data were lack of accuracy in temporal and spatial dimensions, and could not represent thermal and moisture comfort of babies when they were wearing diapers.

3) **Diaper rash grading scale cannot characterize diaper’s thermal and moisture comfort.** Since the causes of diaper rash are complicated, including many other factors such as baby maturity, number of urinations/defecations per day, breast-fed or not, and diaper changing frequency [26, 27]. Besides, these factors are quite difficult to control in clinical trials. Therefore, diaper rash grading scale is not inappropriate to characterize thermal and moisture comfort of diaper.

Due to ethical and safety considerations, in current evaluation research on thermal and moisture comfort of diapers, it is generally not recommended to invite real baby subjects for wear trials except some clinical medical researches to investigate etiology of diaper rash and its influencing factors.

#### 4.2. Manikin wear trial

With rapid development of manikin technology, in order to obtain the real-time thermal and moisture properties in diaper’s wearing state, some researchers have developed partial or full-scale baby manikins for evaluation of diaper products, and the most representative ones are shown in Table 3.

### Table 3. Related parameters of partial or full-scale baby manikins.
According to Table 3, due to different research purposes, there were large differences in manikin parameters, postures and control modes in these studies. The relevant analysis is as follows.

1) **The simulation of real babies needs to be improved.** It required reasonable data for reference and mature technology support to precisely simulate the physiological characteristics such as baby’s shape, length, movements and thermoregulation mode. First, the shape and length simulation must reach an average development level at corresponding month-old baby. Then, settings of manikin postures and activity levels should come from observation of baby’s daily behaviors. Besides, babies are less able to regulate their body temperature than adult, and this regulation pattern also changes with age, so further research is needed to investigate baby’s unique thermal physiological mechanism and establish a thermal regulation model coupled with baby manikin system. However, baby manikins applied in these studies had different characteristics and not formed a standardized measurement system yet.

2) **More influencing factors need to be explored.** Fukazawa [8] studied the influence of dual factors (with/without elastic belt in the fastening system, urination frequency) on water vapor pressure of the microclimate in the diapers. Satsumoto [9] considered the combined influences of multiple factors (diaper type, walking speed, air permeability) on local ventilation in different sites of diaper. And Zhang [1] discussed the influence of a single factor (urination frequency) on temperature and humidity in different sites of diaper. They usually ignored the influence of dynamic changes of micro-space underneath the diaper on microclimate parameters in their analysis of influencing factors. However, the size of the micro-space deserves a further investigation because it has a close relationship with baby’s urine volume, postures, ease allowance of diaper, and the expanding characteristics of diaper materials.

![Figure 4. Diaper covering zones of baby manikin Ruth (13-Torso Front Lower; 14-Torso Back Lower; 15-Diaper Zone).](image)

In 2017, Thermetrics LLC (Seattle, WA), which has advanced manikin manufacturing technology, developed a baby sweating thermal manikin *Ruth* with the size of a 9-month-old baby [28]. After that, technical optimizations were performed to divide the area covered by diaper into three zones (nineteen zones in total), as shown in Figure 4.
Ruth can be used for evaluation of thermal and moisture properties of diapers in their wearing state, and provide powerful technical support for evaluation research of diapers. Although some researchers have already taken the baby thermal manikin as a common standard equipment to measure thermal and moisture properties of fabrics such as baby clothing and bedding [29–31], there are still no testing standards specifically applicable to baby manikin. So, they referred to relevant testing standards applicable to adult thermal manikin in their studies, such as ASTM F1291-16 [32], ASTM F2370-16 [33], and ISO 15831:2004 [34]. In these standards, thermal and evaporative resistance are used to characterize thermal and moisture properties of clothing. However, diapers have some characteristics both in material and structure that are different from clothing, which will cause some problems when using test methods of thermal and moisture properties for clothing. For example, when measuring evaporative resistance of diaper products, it is recommended to test under isothermal conditions and dress the manikin a piece of wet fabric “skin”, which is kept saturated throughout the test. If this method is used for diapers with high water absorption capacity, it is extremely difficult to keep the “skin” saturated and will cause the actual evaporative resistance overestimated, when the manikin is wearing the “skin” and a diaper at the same time. And this problem has been confirmed in previous studies [35]. Therefore, if the general test methods of measuring garments are used for diapers, we need to consider the influence of strong moisture absorption capacity of diaper materials on test results. It is recommended to develop the fabric “skin” with water-proof outer layer and moisture-permeable inner layer specifically for diaper evaporative resistance test, or set proper sweating rate for diapers.

5. Numerical simulation of heat and moisture transfer process in diapers
Compared with evaluation methods with the help of experimental equipment, numerical simulation method has advantages of lower operation cost and wider application range. More importantly, it can solve complex problems that cannot be solved by theoretical analysis, and has more flexibility than physical experiment to predict relevant parameters [36]. Numerical simulation is often used in the field of clothing comfort, with a relatively mature development. For baby disposable diapers, their dual particularities both in clothing and wearer, will indeed bring many limitations to physical experiment. Therefore, in the area of evaluation for baby diapers, numerical simulation can get rid of these limitations to some extent.

At present, numerical simulation on heat and moisture transfer process of baby disposable diaper is still in its infancy. In the simulation on liquid moisture management process of diaper materials, some researchers regarded the absorption core of diaper as a porous media containing absorbent gelling materials, model the unsaturated flow, liquid absorption and large deformation processes [37–39], and consequently increase liquid absorption by diaper materials optimizations. In the simulation on heat and moisture transfer process of diaper products, Japanese scholars used finite element method to predict diaper shape and air layer thickness distribution between diaper and skin while worn [37, 38], but only used the predicted shape and size of micro-space for baby’s contact and pressure comfort research. Researchers from The Hong Kong Polytechnic University predicted and visualized temperature and humidity at the skin and each layer of a diaper based on a software platform (S-smart system) [42]. However, these studies did not consider that due to urine absorption, dynamic changes in shape and size of diaper materials as well as the micro-space would cause microclimate change between diaper and baby skin. Therefore, in the future, numerical simulation methods in related fields need to be established on conclusions drawn from physical principles, empirical formulas and a large amount of evaluation data. In summary, it is urgent to explore various factors influencing thermal and moisture comfort of diapers by physical experiments, analyze the relationships among them, and establish systematic evaluation and characterization methods.

6. Limitations and future work
Based on the analysis of heat and moisture transfer mechanism in the wearing state of diapers, current evaluation technologies of thermal and moisture comfort of baby disposable diapers were summarized from material and product perspectives. Limitations of previous studies are as follows.
The particularity of diaper material/product that is different from conventional fabric/clothing is lack of attention. Actually, disposable diapers are not thick garments. It has multi-layer non-woven materials with high water absorption capacity, and a relative closed structure while worn. Moreover, the shape and thermal/moisture properties of diaper materials will change after absorption. On one hand, its thermal conductivity increases as well as air permeability decreases; on the other hand, its volume expands while weight and thickness increases. So, in some cases, conventional fabric/clothing evaluation methods are not suitable for diaper material/product. For instance, it is difficult to obtain accurate and effective results of indicators such as water vapor transmission rate of diaper materials, and evaporative resistance of diaper products.

The simulation of experimental scene and baby manikin is lack of reasonable references and uniform parameters. We found that this problem is especially reflected in material compression, urination simulation and manikin parameter and mode settings. For example, the pressure devices varied greatly in different standards, so did the setting of pressure parameters. Since the construction of various baby manikins or devices are different from each other, systematic evaluation approaches and standards have not formed yet at present.

The relationship between thermal and moisture comfort and baby skin damage has not been studied and established. Although a lot of baby clinical trials indicated that the change of skin wetness and pH caused by diaper after wearing for a period of time is likely to cause skin damage, further research is required to explore the relationship between skin physiological data or diaper microclimate data while worn and skin damage.

As a result, evaluation of diaper’s thermal and moisture comfort should be focused on the following aspects in the future.

1) It is required to focus on shape and properties change of diaper materials and dynamic change of micro-space size underneath the diaper after liquid absorption. Micro-space underneath the diaper may become an important entry point to study on evaluation of diaper’s thermal and moisture comfort in the future.

2) Technical improvements are needed to make evaluation experiments more closely to real life scene and manikin system more standardized. This will be helpful to increase the effectiveness and accuracy of test results.

3) It needs to be clear that to accurately predict baby skin damage is one of the research goals. The original intention of evaluation research was not only to optimize diaper products, but also to prevent health problems caused by thermal and moisture discomfort of baby skin. Therefore, introducing professional knowledge such as baby skin physiology, and applying non-contact approaches to collect baby skin physiological data are both possible effective methods.

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