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Entropic Assessment of Sleeping Comfort

D. Kayali[1], Y. Yavuz[2], B. Yilmaz[3], M. Özilgen[4*]

[1,4] Yeditepe University, Department of Food Engineering, 34755 Atasehir, Istanbul, Turkey
[2,3] Yeditepe University, Faculty of Medicine, Department of Medical Physiology, 34755 Atasehir, Istanbul, Turkey
E-mail: [1]denizkayali98@gmail.com, [2]yavuz.yavuz@yeditepe.edu.tr, [3]byilmaz@yeditepe.edu.tr,
[4*]mozilgen@yeditepe.edu.tr

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Abstract

In the literature longevity and comfort are evaluated in terms of entropy generation and export rates. When people cannot export entropy, they experience discomfort. Effect of bedding, pajamas and levels of body coverage have been assessed in 270 cases by referring to body weight and height of 25 years old women. By 160 cm tall and 50 kg women, at 0 °C of room temperature, entropy export rates were $6.0\text{x}10^{-3}$ and $7.4\text{x}10^{-3}$ W/kg K, while they were sleeping on their back and on the side, respectively. The results showed that entropy export became more difficult as the body temperature approached the room temperature. Textile properties, including heat transfer and wicking rates of sweat removal were also important while exporting the entropy. The results of this study may be employed while designing beds or beddings, pajamas and comforters to achieve a more comfortable sleeping environment.

Keywords: *Sleeping preferences; metabolic heat generation rate; entropy generation rate; sweating, heat transfer rate; woolen and cotton pajamas.*

1. Introduction

1.1. Physiology of sleeping

Adult humans need approximately 7-8 hours of night sleep to be active during the day and to avoid illness such as cardiovascular diseases, diabetes, stroke and dementia [1]. Organisms live at far-from-equilibrium with their surroundings while maintaining homeostasis, importing exergy and exporting entropy [2]. Homeostatic mechanisms (mechanisms, which keep the internal conditions of the body constant) generate switching impulses to initiate sleep when a person is awake for a long time. In 24 hours of daily cycle, wakefulness and sleep stages are kept in balance with homeostatic effects [3]. Autonomic nervous system (ANS), somatomotor system that control the movements of the body and neuroendocrine systems, e.g., the hormonal system that operate under the effect of the neurons, work in co-ordination to maintain homeostasis. The sleep process consists of the deep sleep (non-rapid eye movement, NREM) and the rapid eye movement (REM) phases [4]. ANS activity regulates switches from the awake to sleep and NREM to REM sleep stages. During the NREM sleep, metabolic needs decrease in connection with the decrease in the biological activity and the ANS reflexes; hence, physiological functions (such as heart rate, respiratory frequency, body temperature and metabolic parameters) fall to the lowest level [5]. In NREM sleep, parasympathetic system is more active than sympathetic system. In the REM sleep, phasic cardiovascular events develop and thermoregulation is suppressed, the ANS becomes unstable because of the phasic changes in sympathetic and parasympathetic discharges. Circadian regulation of sleep and other body functions is processed by neurons located in the hypothalamic suprachiasmatic nucleus (SCN) [5]. Signals from the thermoreceptors are transmitted to the brain that collateralize to the lateral parabrachial nucleus (LPB) in the brain stem and thalamus [6]. Thermal information received in the thalamus is relayed to the somatosensory cortex, where it mediates the perception and discrimination of temperature [7]. Thermal input to the LPB is projected to the neurons in the hypothalamic preoptic area (POA) where thermoregulation is processed to maintain a stable core body temperature [8].

The sleep-wake cycle is associated with heat loss and heat generation during the circadian cycle. In the first half of the night's sleep, energy expenditure and body temperature decrease gradually and then remain constant in the other half. Energy expenditure decreases during sleep, but when the sleep phases are evaluated within themselves, more energy is spent during REM compared to NREM, since the brain activity is higher during REM [5]. Sleep and wakefulness are regulated by different brain regions. The brain-stream-neurotransmitter systems such as noradrenaline, acetylcholine, serotonin and dopamine project to various parts of the brain to support wakefulness [9]. The hypothalamus plays important roles in three basic processes related to sleep. The first includes the SCN and controls the circadian cycle. Secondly, it is the chief regulator of the ANS that controls several vegetative functions including the body temperature [10]. The third role involves production of histamine and orexin neuromodulators that promote wakefulness.

All sensory information is transmitted through thalamus then projects to the brain cortex (except a part of the olfactory sensation that directly feeds to the sensory cortex)

*Corresponding Author

[11, 12]. Continuous flow of sensory input to the brain cortex is important to maintain consciousness. During sleep, transmission of sensory information to the brain cortex is reduced.

Changes in the body temperature follow a sinusoidal rhythm, and the core body temperature reaches a minimum value between 04:00-06:00 am under physiological conditions. The transition to sleep is closely related to the core body temperature, and the minimum decrease in core body temperature begins 5-6 hours before falling sleep. Reduction of the core temperature overlaps with maximum sleepiness in circadian rhythm. Wakefulness occurs 1-3 hours after the minimum body temperature begins to rise within the physiological range [13].

Melatonin is an indolamine hormone produced by the pineal gland and released into blood circulation [14]. It has a circadian rhythm and released during the dark phase of the day, reaching a peak between 02:00-04:00am. Serum melatonin levels start to increase 2-3 hours prior to sleep and reaches its maximum level during the middle of sleep. Melatonin secretion decreases after waking up (i.e., when light falls on the retina) and reaches to its minimum levels during the middle of the day [15].

1.2. What is the resting energy expenditure?

More than half of the daily-consumed energy is the resting energy expenditure. In the resting state, energy is used for the maintenance of vital functions. While 20-30% of the energy expenditure is for voluntary activity, 5-10% is spent for thermogenesis. The main methods used in energy expenditure measurement are direct calorimetry, indirect calorimetry and predictive equations. Indirect calorimetry is based on the energy consumed by measuring the amount of oxygen consumed and the amount of carbon dioxide produced. The resting energy expenditure constitutes about 60-75% of the total daily energy expenditure. Energy expended during the rest is spent on basal metabolic processes. The key indicator is the lean mass. For this reason, it is less in women than men are and in the elderly compared to young people. The thermal effect of food and physical activity increase resting energy expenditure [16]. Lean mass consists of bones, skeletal muscles, active organs such as the brain, heart, liver, kidney, and digestive organs. High cardio-pulmonary work increases resting energy expenditure [17]. The time spent in the initiation and in the following stages of sleep affects the metabolism. Energy expenditure and RQ increase during slow wave sleep, NREM's first and second stages, REM and wake after sleep onset. While RQ and carbohydrate oxidation decreases in the first half of sleep, it increases in the second half of sleep [18].

1.3. What is thermoregulation?

Thermoregulation involves both behavioral and autonomic processes. Tremor and sweating are behavioral responses superimposed on the autonomic responses [19]. In order to maintain the core body temperature, heat gain and heat loss must be in balance. During removal of heat from the body, blood flow from the core to the peripheral areas increases. Therefore, heat transfer per unit time increases and a positive thermal gradient occurs. Heart rate and heat production are directly proportional in active state [3]. Prior to sleeping, the core-body temperature declines and heat is dissipated out. Vasodilation (enlargement of the veins) occurs in the arteriovenous anastomoses and blood flow increases and heat is removed from the body. Arteriovenous anastomoses are available intensely in the distal areas of the body, such as hands, feet, nose, ears and lips [15]. They maintain the core body temperature. They are affected by environmental temperature and behavioral factors. While thermoregulation is active in the NREM process, it gradually decreases during the REM process. Responses such as sweating or shivering are generated against environmental conditions. The need to sleep and the first stage of NREM is associated with a decrease in core body temperature and an increase in peripheral body temperature. While awake, proximal temperature is higher than distal temperature. As desire to sleep increases, core temperature declines, distal temperature increases, and the two of them become almost equal and sleep begins at the point where they are equal. Melatonin hormone plays a role in the occurrence of these changes and as a result induces hypothermia (decrease of the body temperature) [20]. It is known that hypothermia occurs also during anesthesia [21].

1.4. Sensory perception of thermal stimulation and central control

Thermoreceptors transform cold and warmth stimuli into action potentials that are transported to the central nervous system [8, 12]. The thermal signals are first transmitted to the spinal cord and projected to the sensory cortex through thalamus. The hypothalamus receives input from the LPB and functions as the brain center that integrates peripheral and visceral thermal signals and maintains the body temperature [3]. Neurons in the POA of the hypothalamus serve as the thermostat that process, regulate heat loss, and heat gain mechanisms.

1.5. Efferent responses

When POA receives an unusual heat input, it generates an error signal and initiates homeostatic responses [3]. Input coming to POA is transmitted to physiological and behavioral effectors via rostral medulla. Neurons originating from the medulla activate peripheral sympathetic and parasympathetic responses. Physiological effectors affected by neurons are brown adipose tissue thermogenesis, control of skin blood flow, tremors and evaporation [8].

1.6. Respiration

At the beginning of sleep, air volume, inspired / exhaled per minute rate (minute ventilation) and tidal volume decrease. During NREM, ventilation is regular, there are no obvious changes, and minute ventilation is gradually reduced. During REM, the respiratory rhythm is irregular [5].

1.7. The effect of ambient temperature on sleep?

Warm environments negatively affect sleep quality [1]. Thermal comfort depends primarily on the microclimate of the bed and secondly on the ambient temperature. Warm environment affects sleep worse than cold environment. The sleeping set reduces the temperature change of the bedding environment and improves the sleep quality [4]. Sleep quality depends on the thermal insulation of the bedding microclimate rather than the ambient temperature. Bedding microclimate with good thermal insulation protects sleep quality [22].

1.8. Effects of cold environment

When the thermal insulation of the bedding environment is insufficient, the cold ambient temperature negatively affects the sleep quality [22].

1.9. Effects of warm environment

High ambient temperature decreases the sleep, the REM, and the slow wave sleep (SWS) times, and increases falling asleep time and awareness. Additionally, adaptation to sleep is low at high temperatures [23].

1.10. Bedding Environment

The sheets used, the clothes worn and the percentage of the body covered by these covers change the total insulation of the bedding system. Therefore, the insulation of the sheets affects the indoor thermal neutral temperature for the sleeping person [23]. Thermal properties of bedding and sleeping clothes should be steady state and permeable to ambient temperature. The microclimate of naked sleeping persons consists of skin and sheet. In the case of wearing sleepwear, there are two microclimates; one is between the skin and the sleepwear and the other is between the sleepwear and the sheet [4]. The human body needs to maintain its core temperature between 36.0 and 37.5 °C for physiological functioning. When the core exceeds this range, eccrine sweat glands begin to produce sweat. When the skin is not clothed, evaporation of the sweat absorbs 2.4 kJ of heat per gram and cools the body. However, when the body is clothed, the sweat may wick into the clothing. In such a case, evaporation slows done, and the cooling efficiency is reduced [24].

1.11. Heat and entropy generation while sleeping

Heat is generated within the body in association with metabolism [25]. The "*entropic age*" concept suggests that ageing related changes in the body, such as loss of molecular functions and overwhelming of the maintenance systems, may be explained in terms of entropy generation [26, 27]. Silva and Annamalai [28] and Annamalai and Silva [29] made significant contribution to this area of research by quantifying the entropy generation related ageing stress on individual organs. Maintaining easy release of $\dot{q}$ has been an active research topic to evaluate human comfort at different temperature and humidity levels [30, 31] by each gender (Molliet and Mady 2021) [32]. Most of the body heat is dispersed into the universe, and the fraction of it, which causes the cellular damage, reveals itself as entropy accumulation [33, 34]**.** Entropy, which is generated this way throughout the life span is called "*life span entropy*" and associated with life expectancy.

1.12. Sweating

Sweating is controlled by the hypothalamus. It allows the body to release excessive heat via evaporative cooling at the skin. Heat absorbed by the blood at the core of the body is transported to the skin and then removed via evaporation. While the body attempts to cool down with evaporative cooling, its response to high temperature is similar to its response to fever [35], where vasodilation and increased heart rate and contractility to support the heat transfer. It has been reported that sweating is less in REM process. In NREM process, the higher the ambient temperature, the higher the skin temperature and the sweating rate [4]. In the present study, effect of sleeping preferences on the caloric expense and entropy generation of 25-year-old women will be evaluated by referring to 270 different cases. The height and the weight of the women will be referred as the biological parameters, sleeping on the back or on the side, room temperature, coverage of the body with woolen or cotton pajamas or comforter and the heat transmission properties of the bed as the sleeping preferences.

2. Methods

Calculations were carried out for 25 years old women, who were 1.60, 1.70 and 1.80 m tall and 50, 55 and 60 kg, respectively. They were covering 30, 50 or 70% of their bodies with 0.8 mm thick woolen pajamas and comforters at 0 and 10 °C and 0.8 mm thick cotton pajamas and comforters at 20 °C. They were wearing cotton pajamas but not using comforters at 30 and 40°C while sleeping. The pajamas had a thickness of 0.80 mm; thermal conductivity of wool was 50.4 mW/m K, heat transfer coefficient 60 W/m^2 K. The thick wool comforter had a thickness of 37.3 mm, thermal conductivity of 39.9 mW/m K, and heat transfer coefficient 10.7 W/m^2 K. Thin cotton comforter had a thickness of 0.8 mm. Temperature of the room, where they slept was 0, 10, 20, 30 or 40 °C and there was no moisture accumulation in the rooms. Heat transfer coefficients of the fabrics were adapted from Holcombe and Hoschke [36]. Natural heat transfer coefficients of different parts of the body were obtained from De Dear et al [37].

At 0, 10, 20 and 30 ℃ Eq 1 was employed to describe heat transfer from the body, under these conditions temperature difference between the body and the environment was the driving force for the heat release from the body and sweating was not an effective heat transfer mechanism at these temperatures. At 40 ℃ environmental temperature was above the body temperature; therefore, evaporative cooling was considered as the dominant mechanism at this temperature. First law of thermodynamics has been employed to describe the energy balance around the sleeping women in (**Figure 1**):

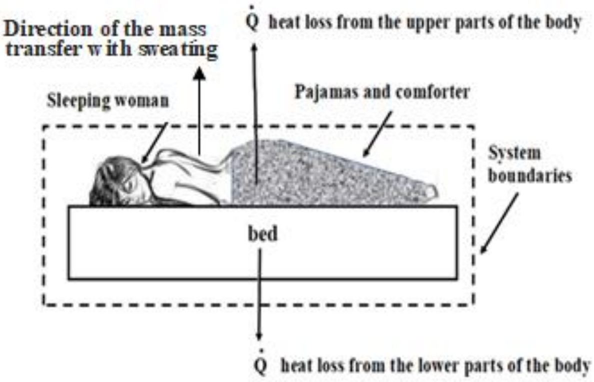

Figure 1. Schematic description of the sleeping woman as a thermodynamic system. In Bed1, Bed2 and Bed3 $\dot{Q}$ pertinent to lower part of the bed is 10%, 20% and 30% of those of the upper parts, respectively.

$$\sum_{in}\left[\dot{m}\left(h+e_p+e_k\right)\right]-\sum_{out}\left[\dot{m}\left(h+e_p+e_k\right)\right]+\sum\dot{Q}+\dot{W}=\frac{d\left[m\left(u+e_p+e_k\right)\right]_{system}}{dt} \quad (1)$$

In **Figure 1**, $\dot{m_{in}} = \dot{m_{out}}$ and e_p and e_k are negligibly small when compared to u; therefore, equation (1) reduces to the following form:

$$\sum \dot{Q} + \dot{W} = \frac{d[m(u)]_{system}}{dt} \qquad (2)$$

When temperature is 30 ℃ or less, Eq 3 describes the heat removal rate from the body:

$$\dot{Q} = U(A)(\Delta T) \qquad (3)$$

Where, U = Total heat transfer coefficient.
A= heat transfer area
ΔT= difference between ambient temperature and body temperature.

Since the surface area, heat transfer coefficients and thermal conductivity of different parts of the body are different, the U values for each part are calculated as:

$$\frac{1}{U(\frac{W}{Km^2})} = \frac{1}{h(\frac{W}{Km^2})} + \frac{x_1(mm)}{k_1(\frac{mW}{Km})} + \frac{x_2(mm)}{k_2(\frac{mW}{Km})} \qquad (4)$$

At temperatures 0, 10, 20 and 30 °C equation (1) describes heat loss from the body, and sleeping related entropy transfer rate due to heat transfer through the surface at these temperatures may be described as

$$\dot{s} = \frac{\dot{Q}}{m\,T} \qquad (5)$$

when temperature is 40 ℃, heat released from the body was adapted from McMurray et al [38], after assuming that all the heat generated in the metabolism is released through sweating. McMurray et al [38] after making a complete review of literature concluded that the mean value for resting metabolic rate was 4.85 W/kg, with 95% confidence limits of 4.79 – 4.91 W/kg. We employed the mean value of the heat released from the body in our calculations.

3. Results and Discussion

Being subject to extremely cold and wet environment causes hypothermia. Shivering is a natural response of the body to hypothermia. When the core body temperature decreases to less than 35 ℃ shivering heats up the body and relaxes the muscles. Basal metabolic rate of the body may increase to compensate the energy loss. Results presented in this study are valid for the cases that the core body temperature do not fall below 35 ℃. The rate of a multi-step cascade-like process would be the same as that of its slowest step [39]. The body temperature is constant, as maintained by the hypothalamus. Height and weight of the women and the apparent heat transfer coefficient U, as described by equation (4), would be influential in determining the heat transfer rates from the body, when conduction and convection are the dominant heat transfer mechanisms. In equation (2) $\dot{W}$ is the internal work performance rate. In the biological systems, work is needed to be done within the system to maintain the essential activities to keep the system living. Work performed by the heart for pumping of the blood or by the lungs for respiration or by the liver for the chemical activities or by the kidneys for re-absorption and secretion processes, along with the electrical work of the nervous system are all regarded as the internal work. In addition, the synthesis of the entire mass of muscles and the bones are some examples to the "*internal work*". At environmental temperatures between 0 to 30 °C the body may be able to perform more internal work than that of 40°C in addition to exporting heat. At 40°C, the body may experience a heat shock. The body responds to heat shock by expressing heat shock proteins, to help prevent or reverse protein misfolding and provide an environment for proper folding [40]. At 0, 10, 20 and 30 ºC there was heat transfer between the body and the room, however at 40 ºC there was mass (sweat) transfer from the body to the room through the pajamas and the bedding, evaporation of the sweat cooled the body.

In the present study, heat removal rate from the surface of the body was regarded as the rate-limiting step. **Figures 2-4** include two different modes of heat transfer from the body. At 0, 10, 20 and 30°C heat removal from the body was achieved via conduction and convection from the skin; whereas at 40°C heat removal was achieved with evaporative cooling from the skin. There was no sweating at 0, 10, 20 and 30°C. Heat transfer with conduction and convection from the skin is a passive process, where the body does not need to perform extra work. However, evaporative cooling is an active process; at 40 °C, heat is transported from the core to the surface with increased rate of blood circulation, which require an additional work performance by the body [41].

Figures 1-4 show that at 40°C substantially higher heat is removed from the body and substantially higher entropy is generated. Pajamas and the beddings considered in this study were made of natural fibers with wicking ability [24]. Those fabrics transport sweat to the surface with wicking and were assumed not to interfere with the heat removal process. The mechanism of the heat transfer would be substantially more complicated and the results of this study would be substantially different, if synthetic fibers, with no wicking ability were employed in this study. At 40 °C, heat release by 25-year-old 160 cm tall, 50 kg women is 242.5 W; by 170 cm tall, 55 kg women is 266.75 W and by 180 cm tall, 60 kg women is 291 W. Specific entropy generation rates by all of these women is constant and 15.57×10^{-3} W/kg K.

People generally prefer sleeping on the side [42]. Schrödinger [43], Prigogine and Wiame [44] and Demirel [45], Yildiz et al [2] among many others, argued that organisms live at far-from-equilibrium by up taking energy or exergy, and exporting entropy. Entropy may be regarded as the unusable energy dissipated through molecular vibrations [46] and exporting entropy may be considered as a type of pollution [47]. Both exergy analyses and entropy generation are based on the second law of thermodynamics. Özilgen [48] evaluated the comfort related studies in detail in his review on biothermodynamics and indicated that the pioneers of these studies were air-conditioning engineers. Aoki [49, 50] focused on entropy removal from the environment as the purpose of comfort studies. This approach has been followed by many others. Lucia and Grisolia [51] described in detail that exergy destruction in a process could be calculated as the product of the environmental temperature and the irreversibility related entropy generation. In the present study, we preferred following the Aoki's approach.

Figures 1-4 show that more entropy is exported from the body, when people sleep on their sides. Entropy generation rates by 160 cm tall, 50 kg and 25 years old women are compared in Figure 2. At 0℃ of room temperature, entropy generation rate is less in the case of sleeping on the back (Figure 2a) than that of the case of sleeping on the side

(Figure 2b). At 0 degree of room temperature, entropy generation rate is 6.0x10^{-3} W/kg K while the woman is sleeping on her back and 7.4x10^{-3} W/kg K while sleeping on the side. Difference between both sleeping positions is not negligible. As the room temperature increases, entropy generation rates decreased. When the room temperature is reached 30℃, entropy generation rates are nearly same for both sleeping positions and the difference is negligible. At 30℃ of room temperature, entropy generation rate is 1.2x10^{-3} W/kg K while she is sleeping on her back and 1.4x10^{-3} W/kg K while sleeping on her side. As the room temperature increases, entropy generation rates increase for both sleeping positions. When the room temperature reaches to 40℃, entropy generation rates are same in both sleeping positions. At 40℃ room temperature, entropy generation rates are 15.57x10^{-3} W/kg K for both sleep positions.

In Figure 3, comparison is made for different sleeping position and bed preferences for a 170 cm tall, 55 kg, 25-years-old women. In **Figure 3a**, while she is sleeping on her back, entropy generation rate increased as the heat permeability of the bed increased at 0℃ of room temperature. For bed1 with the heat permeability of 0.1, the entropy generation rate is 5.4x10^{-3} W/kg K, and the entropy generation is 6.3x10^{-3} W/kg K in bed3 while heat transfer rate from the bed is 30% of that from the upper sides of the body. Entropy generation rate is 6.3x10^{-3} W/kg K for bed1 while heat transfer rate from the bed is 10% of that from the upper sides of the body and 7.4x10^{-3} W/kg K with bed3. For both sleeping positions, as the room temperature increased, the entropy generation rates decreased, regardless of the bed preferred. When the room temperature is 30℃, entropy generation rates are almost the same, when different beds are preferred in both sleeping positions. At 40℃ of room temperature, entropy generation rate is the same and 15.57x10^{-3} W/kg K for both sleeping positions in all types of beds.

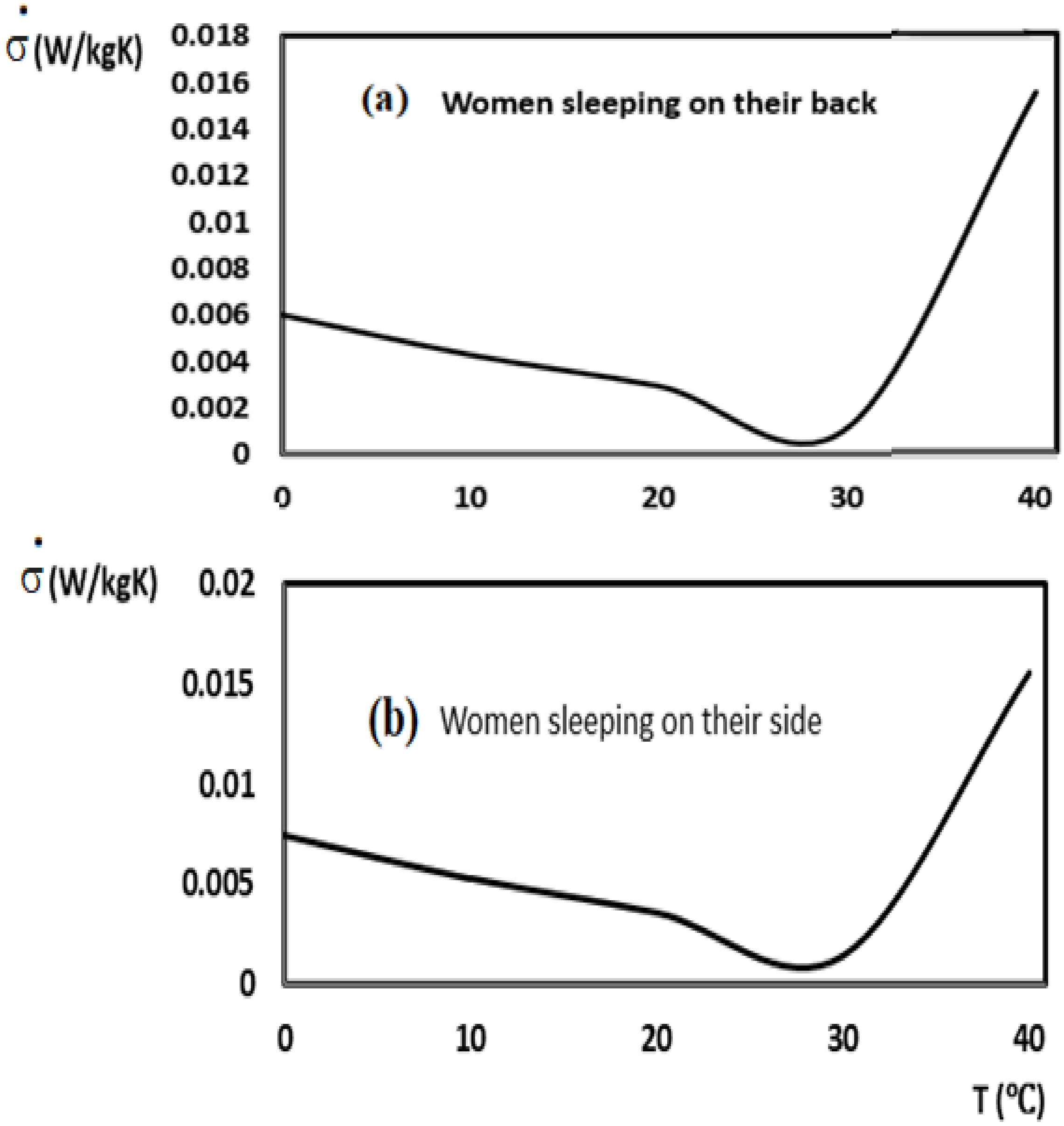

*Figure 2. Specific entropy generation rate versus the room temperature, when 160 cm tall, 50 kg and 25-year-old women sleep on their back **(a)** and on their side **(b)** in bed1 when ϕ=0.30.*

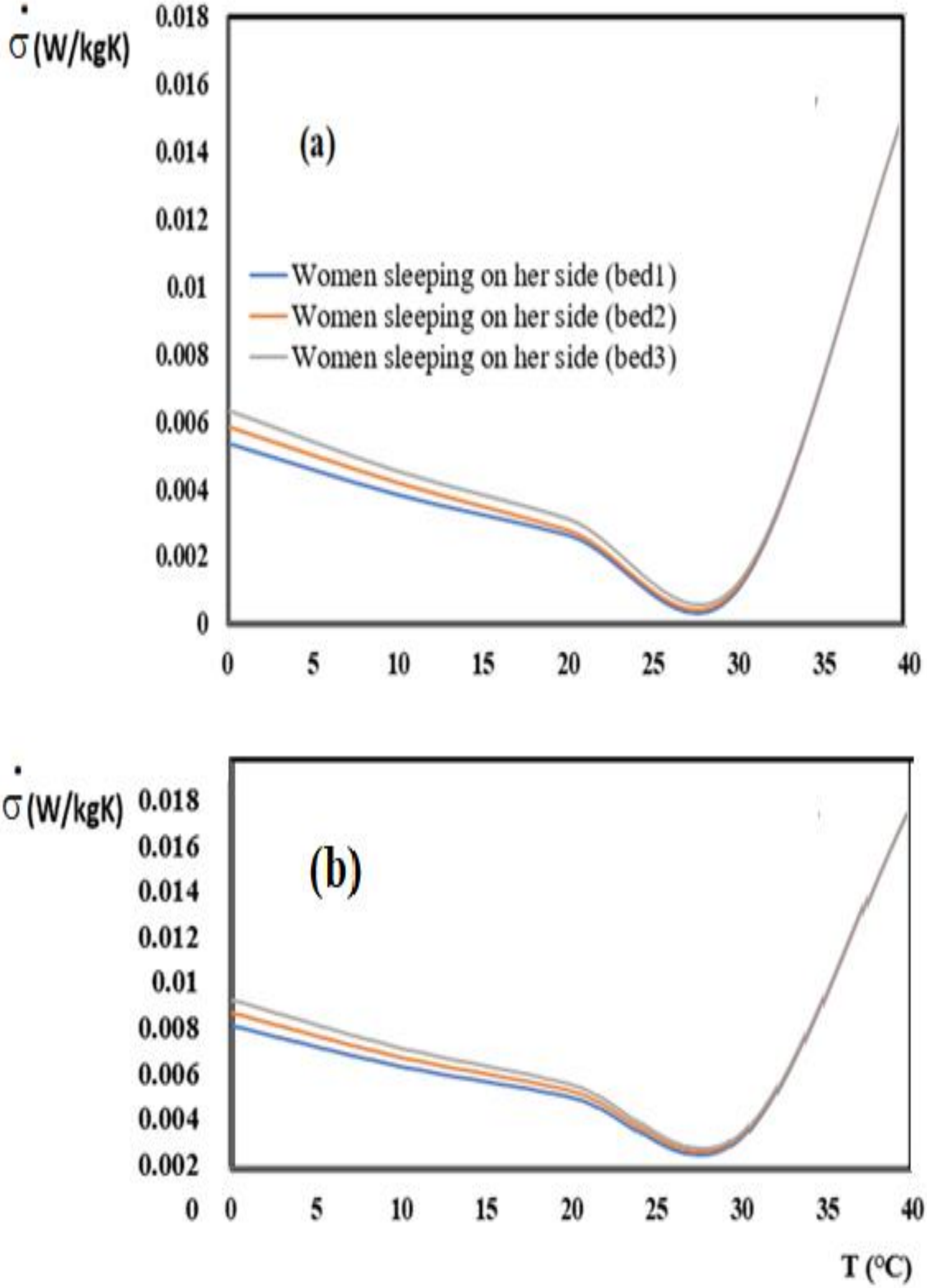

*Figure 3. Specific entropy generation rate versus the room temperature when 170 cm tall, 55 kg and 25-year-old women sleep on their back **(a)** and on the side **(b)**, in bed1, bed2and bed3 when ϕ=0.50.*

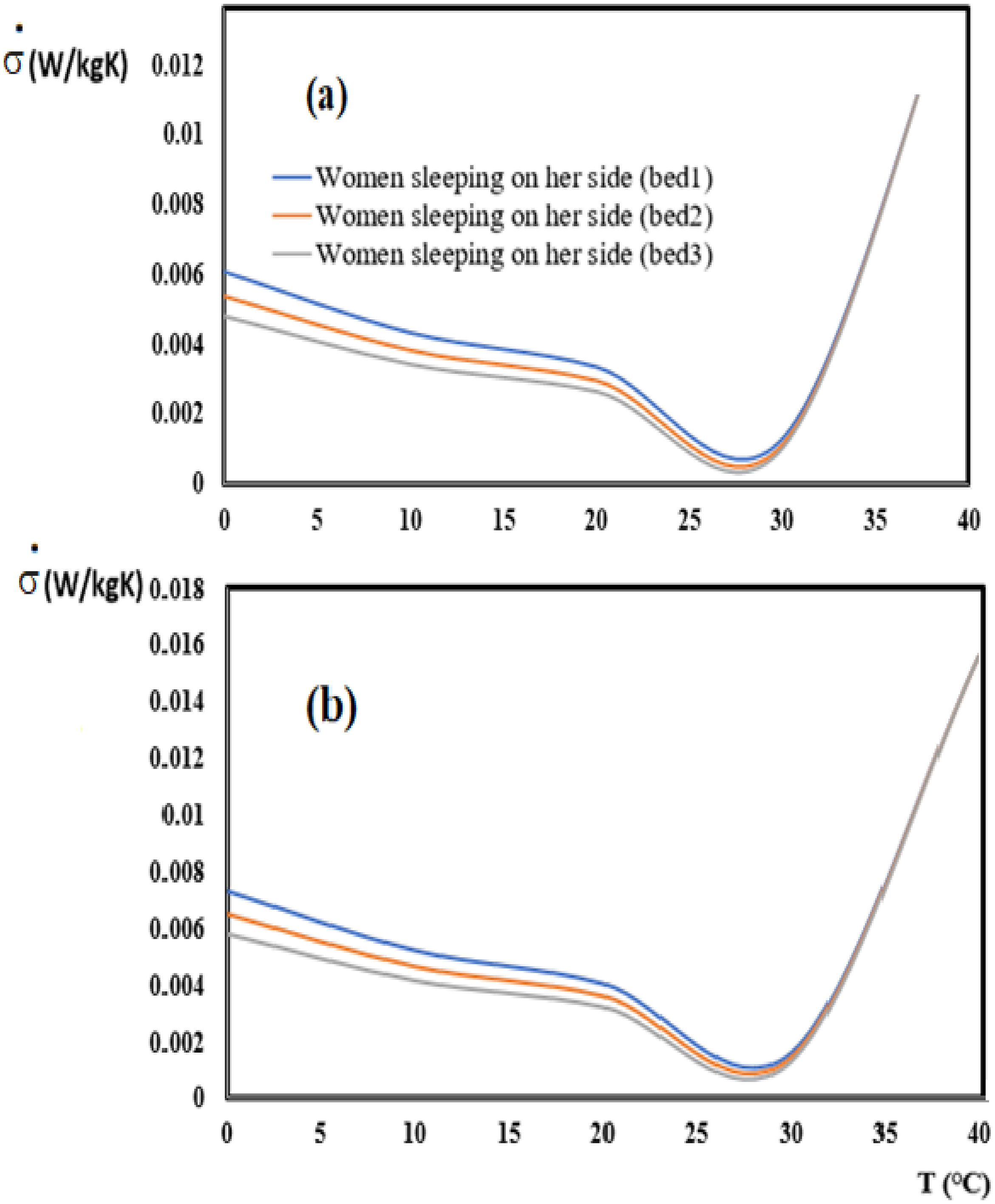

Figure 4. Specific entropy generation rate versus the room temperature, when 25-year-old 160 cm tall, 50 kg, 170 cm tall 55 kg and 180 cm tall 60 kg women sleep on their back ***(a)*** *and on their side* ***(b)*** *in bed3 when ϕ=0.70 (fraction of the body covered).*

Entropy generation rates for 25 years old sleeping women with different body compositions and sleeping positions are compared in Figure 4. At 0°C of room temperature, entropy generation rates decreased as the height and weight of the women increased. For a 160 cm tall and 50 kg sleeping women, entropy generation rate is $6.1x10^{-3}$ W/kg K and for a 180 cm, 60 kg sleeping women, entropy generation rate is $4.8x10^{-3}$ W/kg K. The same conditions are valid for sleeping on her side (Figure 4b). As the room temperature increases gradually, entropy generation rates decrease for every body type and sleep positions. Women with higher height and weight have a lower entropy generation rate for both sleeping positions at 30°C of room temperature, but the difference between them is quite small and may be ignored. When the room temperature increased from 30°C to 40°C, entropy generation rate increases. At 40°C room temperature, entropy generation rate is the same, $15.57x10^{-3}$ W/kg K, for both sleeping positions and all body types.

4. Conclusion

By 160 cm tall old 50 kg old women, at 0 °C of room temperature, entropy exporting rate was $6.0x10^{--3}$ and $7.4x10^{--3}$ W/kg K, while the women were sleeping on the back and on the side, respectively. As the room temperature increased, entropy export rates decreased. When the room temperature reached to 30°C, entropy export rates were nearly the same for both sleeping positions. At 30℃ of room temperature, entropy export rates were 1.2×10^{-3} and 1.4×10^{-3} W/kg K while sleeping on the back and on the side, respectively. At 40℃ room temperature, entropy export rates were 15.57×10^{-3} W/kg K for both sleep positions. For a 170 cm tall, 55 kg, 25-years-old women, while she was sleeping on her back, entropy export rate increased with the heat permeability of the bed. For both sleeping positions, as the room temperature increased, the entropy export rates decreased, regardless of the bed preferred. At 40℃ of room temperature, entropy generation rate was the same and 15.57×10^{-3} W/kg K for both sleeping positions in all types of beds. The results of this study may be employed while designing better comforting beds, sleepwear comforters and bed sheets.

Nomenclature

e_p potential energy entering in to the system or leaving out with $\dot{m}_{in}$ or $\dot{m}_{out}$
e_k kinetic energy entering in to the system or leaving out with $\dot{m}_{in}$ or $\dot{m}_{out}$
h enthalpies entering in to the system or leaving out with $\dot{m}_{in}$ or $\dot{m}_{out}$
h heat transfer coefficient of the naked body $(\frac{\mathrm{W}}{\mathrm{Km^2}})$
k_1 heat transfer coefficient of the pajamas (W/mm
k_2 heat transfer coefficient of the comforter (W7mm)
$\dot{m}_{in}$ input rate of the mass through the system boundaries
$\dot{m}_{out}$ output rate of the mass through the system boundaries (kg)
m weight of the woman (kg)
$\dot{Q}$ = Rate of heat released by the body to the environment (W/m^2)
u chemical energy of the woman (J/kg)
U total heat transfer coefficient from the body $\left(\frac{\mathrm{W}}{\mathrm{m^2}}\right)$
$\dot{W}$ Rate of work performance by the body, since the woman is asleep, the work done equals to the resting metabolic rate.

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