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THERMAL MODEL OF SELECTED PARTS OF HUMAN HAND AND THERMAL TOUCH SCREEN FOR THE BLIND

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Abstract

In this article, the authors present a model and a method of determining thermal parameters of a single point of the thermal touch screen for the blind and thermal parameters of selected parts of a human hand. Blind people, by using this device can "see" a pattern of dots by feeling hot spots. The thermal touch screen for the blind was used as a calorimeter and enables to calculate the amount of heat provided to a finger at a temperature ranging from 8°C to 52°C, that is the full range of temperature detected by humans. The authors designated thermal conductivity and heat capacity of both Peltier micromodule and parts of the user's hand. Results of the presented research allow optimizing the construction of the thermal touch screen for the blind and may be helpful for thermal modelling of the human body.

Keywords: thermal modelling, thermal management, thermoelectric devices.

1. Introduction

The development of science, particularly of electronics in many ways helps the blind people. There are devices in everyday use for reading aloud a printed text, a braille notepad through which they could quickly write braille and then listen to recorded information, braille rulers, talking watches, GPS navigation for the blind [1, 2], mobile phones with a speech synthesizer and many others. Other senses of the blind, especially hearing and touching, are sharper than for people with non-impaired vision. The sounds play an important role in the daily life of blind people in locating their own position or other objects. Most electronic devices for the blind provides information using speech synthesizers. It is a good and proven method, but which unfortunately interferes with the listening environment. The authors developed a device that allows transmission of information by the sense of heat detection. The thermal touch screen for the blind [3] is a device that allows blind people to recognize graphics by touching warm or cold signs. The device is built with the use of 294 thermoelectric coolers (TEC) – Peltier micromodule of size 2 mm x 2 mm each [4] – which work as reversible heat sources. The device can present thermal images easily generated by a PC. By touching the device a user can feel warm or cold points and recognize thermal images. Fig. 1 presents a thermographic image of displayed graphics and a photo of the thermal touch screen for the blind being touched by a blind person. The temperature of every touch point is permanently controlled by feedback, using, inter alia, the Seebeck phenomenon [5].

The designers of a thermal touch screen for the blind need to know the thermal resistance and heat capacity of the skin surface corresponding to the surface of a Peltier micromodule, because they want to control the device in such a way that the thermal sign recognition should be as quick as possible. There are many publications on thermal properties of the human skin

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[6-8]. Nevertheless, knowledge of the specific thermal conductivity and specific heat capacity is not sufficient to designate parameters of a small area of skin because the thickness and volume of the touched skin are unknown.

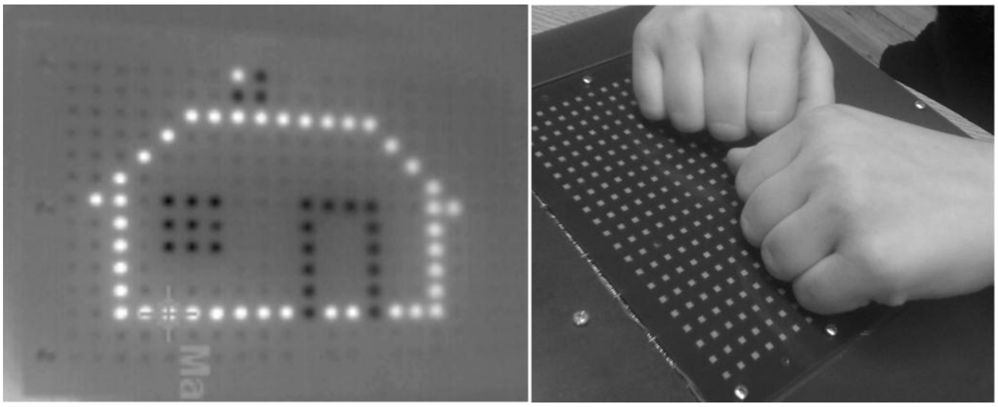

Fig. 1. Thermographic image of displayed graphic and a photo of the thermal touch screen for the blind while being touched. Temperature range 10°C to 52°C.

During normal operation, the user's skin is in contact with many heat points. Heat flows through the skin from one to the other Peltier micromodules. The amount of weight of a finger or hand is so large that heating it by Peltier micromodules is very slow. When the user will feel discomfort from prolongedly touching warm points, it is possible to change the temperature of heat signs to the cold. It is extremely difficult to create an appropriate deterministic model for the entire device due to the varying conditions that occur during use. Therefore, the model determines the thermal resistance and heat capacity of the skin surface and the single heat point. The presented thermal model provides the thermal response of the upper surface of the TEC and the heat flows to the skin, both while touching and turning on the heat point. Static temperature measurements were conducted using the pyrometer. To measure temperature changes of the TEC top surface the Seebeck voltage was used [9].

2. Peltier micropump thermal resistance

During measuring the thermal resistance between the top and bottom surfaces of the Peltier micromodule, the bottom surface was soldered to a very large heatsink. The upper – hot part of the Peltier micromodule was not touched by a finger. Twenty measurements were made, each time with a power supply change in a range from 10 mA to 220 mA. Knowing the heat flux Φ_P that is pumped from the cold-lower to the warm-upper part of TEC, P_J power as the consequence of the Joule law, and the temperature difference ΔT_P between the warm T_P and the cold T_A part of the TEC, the thermal resistance R_{th_P} between top and bottom surface of the Peltier micromodule can be determined as:

$$R_{th\_P} = \frac{\Delta T_P}{\Phi_P + P_J}, \tag{1}$$

$$\Delta T_P = T_P - T_A. \tag{2}$$

The temperature T_P of the hot upper part of the Peltier micromodule was measured by the pyrometer, the temperature of the cold bottom, which is equal to the ambient temperature T_A,

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was measured using a thermistor located on the heatsink. The electrical power P_J was read from the power supply. The values of heat flux Φ_P pumped from the cold surface were calculated using the computer program *TEC CAD 2.1h* [10], provided by the producer of the TEC. These values were read from *Standard Plot* graphs with known parameters: ambient temperature, fixed current and known temperature difference between the warm and cold side of the Peltier micromodule. When the Peltier micromodule is powered below the optimal values [4] then all power P_J generated in the TEC is transported to the warm side. Heat flux $\Phi_{H\text{-}P}$ flows from the heatsink to the upper surface of the Peltier micromodule:

$$\Phi_{H-P} = \Phi_P + P_J. \tag{3}$$

In Fig. 2 the authors present the measured electrical power P_J, heat flux Φ_P and their sum as a function of temperature difference.

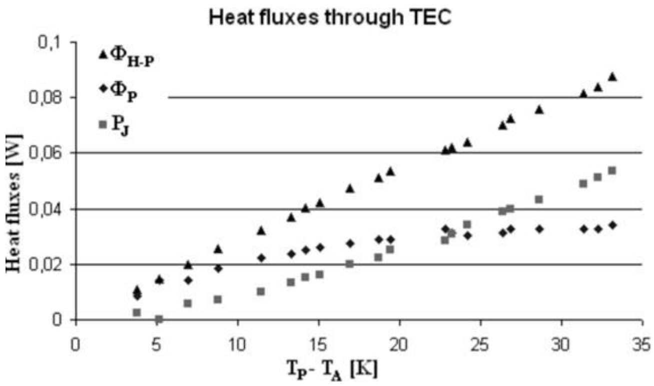

Fig. 2. Measured electrical power P_J, heat flux Φ_P and their sum as a function of temperature difference.

Basing on (1) and the measurements, the authors have designated the value of thermal resistance of the Peltier micromodule as a function of the temperature difference between T_P and T_A.

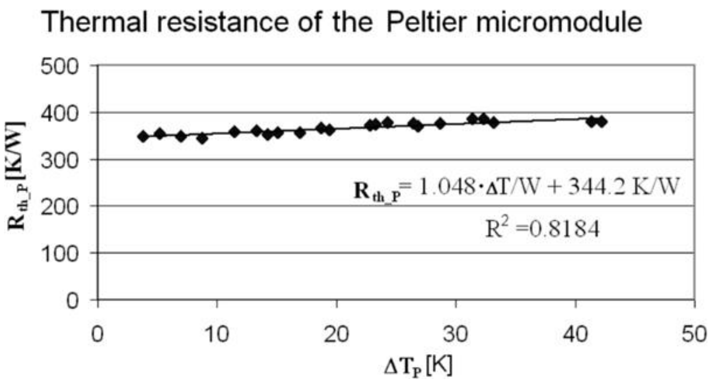

Fig. 3. Thermal resistance of the Peltier micromodule as a function of temperature difference between the warm and the cold side of the Peltier micromodule. Empirical formula, trend line, and the error R^2 are on the chart.

As can be seen in Fig. 3, the thermal resistance of the Peltier micromodule is slightly dependent on temperature difference ΔT_P and equals about 360 K/W for temperature difference 8 K, which equals the temperature of the touch point (32°C), corresponding to an average temperature of the finger skin.

3. Peltier micromodule heat capacity

To determine the heat capacity of the Peltier micromodule, the temperature waveform was measured after turning on the heat point – Fig. 4. The Peltier micromodule is powered by constant voltage equal 0.5 V. The upper-hot side is thermally isolated; the bottom side is soldered to a very large heat sink. The upper surface temperature was determined by measuring the Seebeck voltage at the micromodule, which was periodically switched off and on. Measurements were made every 10 ms. Switch off time that is required to perform the measurement is less than 1% of the measurement period, thus further calculations omit the error resulting from the measurement.

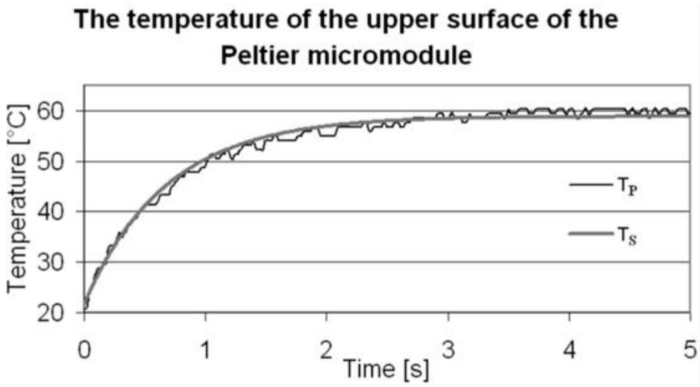

Fig. 4. Temperature of the upper surface of the Peltier micromodule after turning on. T_P - temperature measured using the Seebeck voltage, T_S - temperature simulated in Multisim program based on the model without a finger.

Based on the temperature waveform of the upper surface of the Peltier micromodule, by using the software *TEC CAD 2.1h*, the authors calculated current I_P flowing through the Peltier micromodule and heat flux $\Phi_{H\text{-}P}$ pumped from the cold-to-warm side. Power P_J was calculated at a constant supply voltage, which equalled 0.5 V. Calculations were made only for the eight measurement points possible to measure with the TEC CAD 2.1h. Equations of the trend line of individual measurements and the mean square error R^2 are given in Fig. 5.

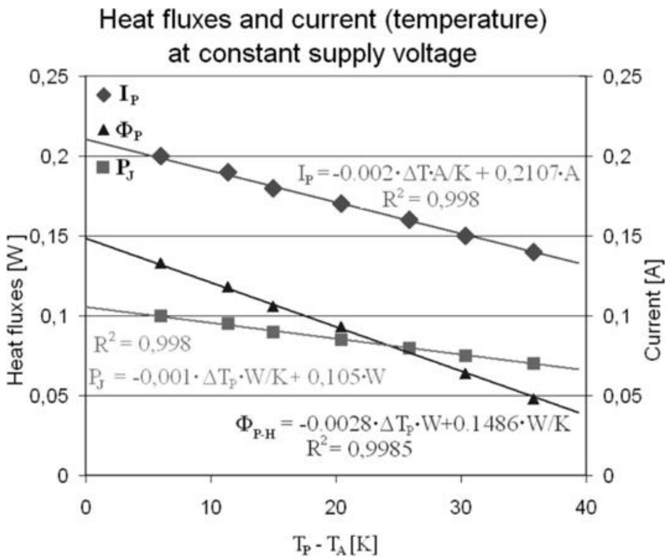

Fig. 5. Values of current I_P, power P_J, and heat flux $\Phi_{H\text{-}P}$ pumped by the Peltier micromodule as a function of temperature difference between hot and cold side of Peltier micromodule. The supply voltage equals 0.5 V.

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As shown in Fig. 5, calculated values are linearly dependent as a function of temperature difference T_P - T_A. Next, by extrapolation, the value of I_P and P_J for the remaining points of the temperature waveform was calculated – Fig. 6. Knowing the temperature waveform T_P and the value of thermal resistance R_{th_P}, the heat flux Φ_{P-H} flowing through the Peltier micromodule to the heatsink was calculated according to (4):

$$\Phi_{P-H} = \frac{T_P - T_A}{R_{th\_P}}. \tag{4}$$

As shown in Fig. 6, heat fluxes Φ_{H-P} and Φ_{P-H} are not equal. The difference of these streams Φ_{C_P} flow into the body of Peltier micromodule with heat capacity C_P.

$$\Phi_{C\_P} = \Phi_{H-P} - \Phi_{P-H}. \tag{5}$$

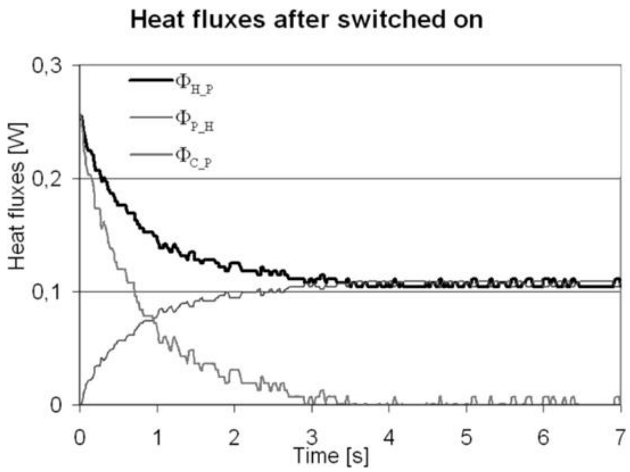

Fig. 6. The heat flux Φ_{H-P} that flows into the upper part of a Peltier micromodule. The heat flux Φ_{P-H} that flows through the thermal resistance of a Peltier micromodule to the heatsink. The heat flux Φ_{C_P} that flows into the body of Peltier micromodule with heat capacity C_P.

The heat Q_P stored inside the Peltier micromodule with the heat capacity C_P is the integral of the heat flux Φ_{C_P} flowing into the heat capacity from the moment *t1* when it was switched on to the time *t2* when T_P achieved a maximum temperature:

$$Q_P = \int_{t1}^{t2} \Phi_{C\_P} \cdot \Delta t. \tag{6}$$

The heat capacity C_P can be calculated from the formula:

$$C_P = \frac{\Delta Q_P}{\Delta T_P}. \tag{7}$$

For this measurement, Q_P = 185 mJ, C_P = 46 mJ/K.

The presented thermal model of the Peltier micromodule is shown in Fig. 7. To provide thermal simulations the authors used a Multisim program, which normally is used to simulate electrical circuits. *I1* and *I2* are current sources simulating the heat flux Φ_{H-P} according to Fig. 5; other electrical components correspond to the appropriate thermal components. The simulation temperature T_S during switching is shown in Fig. 4.

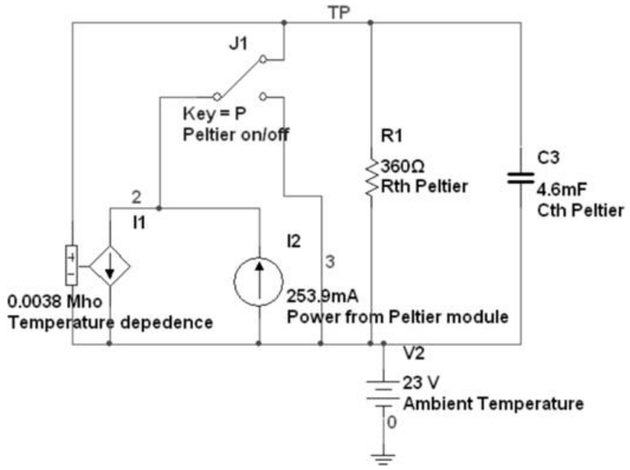

Fig. 7. Thermal model of the Peltier micromodule. $R1 = R_{th\_P}$, $C3 = C_P$, $I1 + I2 = \Phi_{H\text{-}P}$, $TP = T_S$.

4. Thermal resistance of a finger

The thermal resistance R_{th_F} of a finger is represented by thermal resistance between the skin surface of 2 mm x 2 mm that touches a Peltier micromodule, and the inside of the finger. The tester, by using the side of a ring finger next to a fingertip, touched the Peltier micromodule constantly during these measurements. In order to measure R_{th_F} authors performed about 15 measurements of the finger temperature T_F, the current I_P flowing through the Peltier micromodule and the voltage on the Peltier micromodule. Basing on the measured values with the use of *TEC CAD 2.1h* the authors calculated the heat flux $\Phi_{F\_H\text{-}P}$ flowing from the heatsink to the top of the Peltier micromodule. The heat flux $\Phi_{F\_H\text{-}P}$ transported by the Peltier micromodule to the touch surface, is the sum of power P_{F_J} generated as consequence of the Joule law and the heat flux Φ_{F_P} pumped by the Peltier module.

$$\Phi_{F\_H-P} = \Phi_{F\_P} + P_{F\_J}. \tag{8}$$

Measurements were made while the power supply was being controlled in such a way that the temperature T_P of the top of the Peltier micromodule corresponded to measurements performed without touching. For each measurement (with and without touching) temperature T_P was the same.

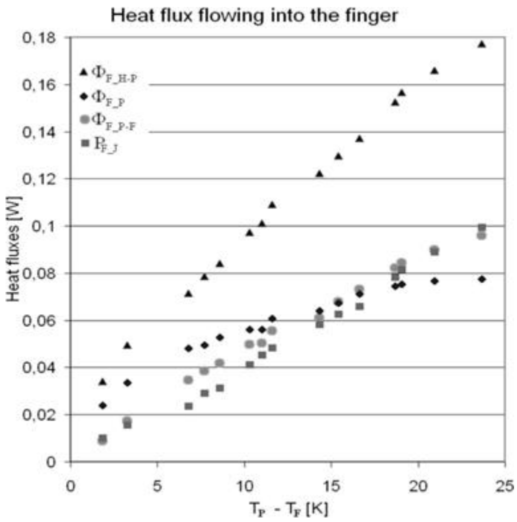

Fig. 8. Heat fluxes: $\Phi_{F\_H\text{-}P}$, Φ_{F_P}, $\Phi_{F\_P\text{-}F}$, P_{F_J}.

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The heat flux $\Phi_{F\_P\text{-}F}$, flowing from the Peltier micromodule to the finger through the R_{th_F} for each measurement of T_P, is equal to the heat flux $\Phi_{F\_H\text{-}P}$ supplied to the upper surface of the touched Peltier micromodule minus the heat flux $\Phi_{H\text{-}P}$ delivered to the upper surface of the untouched Peltier micromodule.

$$\Phi_{F\_P-F} = \Phi_{F\_H-P} - \Phi_{H-P}. \tag{9}$$

Knowing the temperature of the Peltier micromodule T_P, the finger temperature T_F, and the flux $\Phi_{F\_P\text{-}F}$, we can determine the thermal resistance of a finger R_{th_F}, that equals about 220 K/W at T_P = 50°C – Fig. 9.

$$T_{th\_F} = \frac{T_P - T_F}{\Phi_{F\_P-F}}. \tag{10}$$

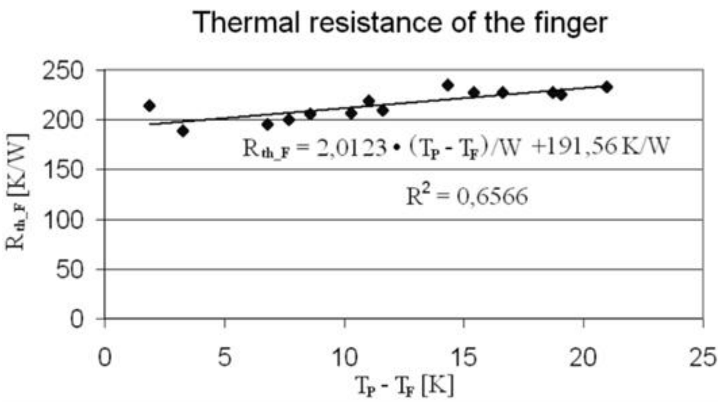

Fig. 9. Measured thermal resistance of a finger as a function of temperature difference T_P - T_F. R_{th_F} is about 220 K/W at T_P = 50°C.

5. Finger heat capacity

The thermal capacity C_F of a part of a finger skin was designated similarly to the Peltier micromodule thermal capacity C_P (by calculating the amount of heat accumulated in the finger). Firstly the temperature waveform T_{F_P} of the upper-warm surface of a touched Peltier micromodule was measured – Fig. 10.

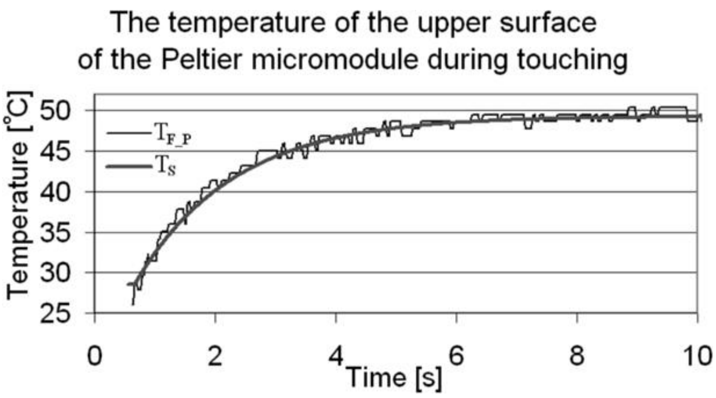

Fig. 10. The temperature of the upper part of the Peltier micromodule measured during switching on, and simulation of this temperature based on the calculated model.

Then, basing on this measurement, the authors calculated the current, the amount of power P_{F_J} and heat flux $\Phi_{F\_H\text{-}P}$. The average finger temperature was 32°C. The sum of heat fluxes Φ_{C_P} + Φ_{C_F} flowing to both the finger and the Peltier micromodule (that have thermal capacities C_F and C_P), is equal to $\Phi_{F\_H\text{-}P}$ reduced by heat streams flowing through thermal resistances R_{th_P} and R_{th_F}.

$$\Phi_{C\_P} + \Phi_{C\_F} = \Phi_{F\_H-P} - \frac{T_P - T_A}{R_{th\_P}} - \frac{T_P - T_F}{R_{th\_F}}. \tag{11}$$

Energy Q_{P+F} accumulated in both the Peltier micromodule and finger with their thermal capacities is the integral of heat flux during charging. The integral was calculated from time *t1* when the temperature $T_P = T_F$ to the time *t2* until T_P reaches its maximum value.

$$Q_{P+F} = \int_{t1}^{t2} \Phi_{C\_P} + \Phi_{C\_F} \cdot \Delta t. \tag{12}$$

The thermal capacity of the finger C_F is expressed by the formula:

$$C_F = \frac{Q_{P+F}}{T_{P\_\max} - T_F} - C_P. \tag{13}$$

Basing on conducted measurements, heat capacity of a finger skin equals 13.9 mJ/K for a surface of 2 mm x 2 mm.

The model used for the simulation is shown in Fig. 11. Using this model, the authors simulated the Peltier micromodule temperature. The result of the simulation T_S is presented in Fig. 10.

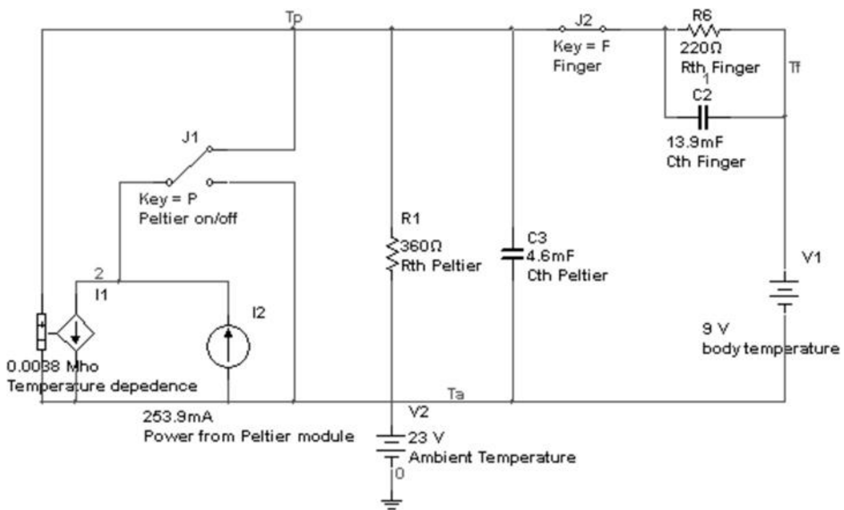

Fig. 11. Thermal model of the thermal touch screen for the blind.

6. Additional measurements

Additional measurements were performed with the help of three subjects who tested the device.

User 1 - a person with slightly thicker fingers,

User 2 - a person with delicate fingers,

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User 3 - a person at age 6.

The device was connected to a supply voltage of 0.5 V (the touch point was heated) or to a supply voltage of 1 V (the touch point was cooled). The difference of supply voltage is the consequence of the fact that the Joule heat is added to the heat transported by the Peltier effect only during heating. Power supply of 0.5 V is insufficient during the cooling. Tests were conducted for selected parts of the hand skin:

a. the side of the ring finger, below the nail,
b. in the middle of the index fingertip,
c. the skin inside of a wrist.

Users selected these parts of a hand while testing the device in the Special Educational Centre for Blind and Visually Impaired Children in Krakow. Measurements presented in Table 1 were carried out when the top surface temperature T_P equalled 50°C and 8°C respectively.

Table 1. Thermal resistance and heat capacity of various parts of a hand.

		Heating C_P = 4.6 mJ/K R_{th_P} = 360 K/W		Cooling C_P = 4.1 mJ/K R_{th_P} = 320 K/W	
		C_F [J/K]*10^{-3}	R_{th_F} [K/W]	C_F [J/K]*10^{-3}	R_{th_F} [K/W]
User 1	a	12.3	260	12	280
	b	11.2	340	11.0	360
	c	13.1	190	12.1	210
User 2	a	13.9	220	13.7	240
	b	11.6	280	11.6	280
	c	14.4	180	14	200
User 3	a	13.1	200	12.5	220
	b	10.8	240	10.7	250
	c	14	170	13.5	170

7. Conclusions

Measurements showed that thermal parameters depend on a person and the part of a hand that touches the device. The thinner the skin and closer contact to the blood, the lower the thermal resistance and the higher the thermal capacity. While testing the device the testers have proven that it is easier to locate a thermal sign using a wrist where heat resistance is the smallest. Although the tip of a finger is used most commonly, it has the highest heat resistance and it is more difficult to recognize thermal characters using this method. The heat capacity of skin is so large that using a simple power supply (which connects TEC to the constant voltage) would cause too slow achievement of set temperature. In addition, such situation would result in instability of heat point temperature while touching. Therefore, in the final device, the temperature of each Peltier micromodule is independently stabilized. The supply voltage is chosen so that the temperature of the Peltier micromodule would reach 55°C after about 300 ms. Without temperature stabilization a touch point would reach a temperature over 160°C. For achieving more efficient heat transfer to the finger, for the next generation of these devices, designers should use the TEC, which has a lower thermal resistance.

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