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Thermal Modeling of Driver/Seat Interfaces in Automotive Applications

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ABSTRACT

A thermophysical model of the dynamic interactions between an automobile driver and a heated seat is presented. The model uses the experimentally measured averaged load distributions to identify the local thermal resistances and to determine variations in temperatures of the seat, the driver's skin and clothing temperatures as a function of time. The model predicts a sudden temperature change in the seat surface temperature in contact areas. However, temperature differences due to the load distribution are found to be insignificant. The effective heat transfer coefficient in the contacted areas is determined to be about 145 $W{\cdot}K^{-1}{\cdot}m^{-2}$ for the contacted areas.

INTRODUCTION

Automobile cabin temperatures can drop to subzero levels during harsh winter conditions. Under such freezing conditions, an automobile driver could experience localized cooling as his/her exposed body surfaces (15 to 20%) make contact with the cold seat, back support and steering wheel. Although the heating system within an automobile attempts to respond to the comfort needs of the driver, the thermal capacity of most cabin components limits the timely response of the heating system, resulting in driver discomfort for extended periods.

While the ambient air temperature is a key factor in evaluating the level of thermal comfort, conductive heat transfer from the driver's body due to contact with a seat that is initially very cold plays a significant role in influencing his/her local and overall thermal sensations.

In recent years, many automobile seats have been equipped with embedded heating pads to enhance drivers' thermal comfort particularly in the initial periods of driving. The generated heat is conducted through the seat cover, and reduces the conduction heat losses from the driver's body in contact areas. This new feature has motivated interest in the development of more efficient driver-seat heating systems to ensure driver thermal comfort under severe winter conditions.

Over the past few decades, several models have been developed to simulate thermal interactions of the human body with the environment. Most of these models are valid in HVAC applications as they consider uniform ambient conditions in their simulations. Excellent reviews and critical evaluations of some of these models can be found in Dohetry and Arens (1988) [2] and Lotens (1988) [6], among others. On the other hand, the study of heat exchange between an automobile seat and its driver is limited, mainly due to the presence of complicated thermal resistance networks resulting from the load distribution in contact areas. Burch et al. (1992) developed a mathematical model of thermal interactions between a driver and the interior environment of an automobile for which good agreement was reported between model predictions and jury data. This model was later extended by Karimi *et al.* (2002) [5] to predict the transient response of a driver in a highly non-uniform thermal environment in terms of local and overall thermal comfort levels. A relatively good agreement was found between the model predictions and experimental data using test subjects [4].

In this paper, more comprehensive physical models are presented to determine the transient thermal interactions between an average driver and a heated seat in contact areas.

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EXPERIMENTATIONS

PRESSURE LOAD DISTRIBUTION

In order to establish a thermal resistance network in the contact areas, the driver's load distribution on the seat should be determined. In this work, a representative driver imprint has been obtained to identify the pressure distribution on a vehicle seat. Two Tekscan™ pressure mats were used to map the occupant pressure distributions on the seat cushion and the backrest, respectively. Each pressure mat was 48 cm wide and 42 cm long and was equipped with 2016 load cells to precisely measure the load distributions.

The study involved 10 participants, of different gender, weight, height, and body size. The pressure data were collected using a data acquisition system over a period of 5 minutes.

Figure 1 displays the averaged pressure distributions on the seat backrest and cushion. The maximum pressures are about 4 and 6 kPa, corresponding to the shoulder area and pelvic region on the seat backrest and cushion, respectively. Pressure distributions are slightly asymmetric with the heavier loads covering a larger area in the right side of the body. The discontinuities in the pressure distributions along lines A and B on the cushion side are due to the elevation change in the cushion side areas.

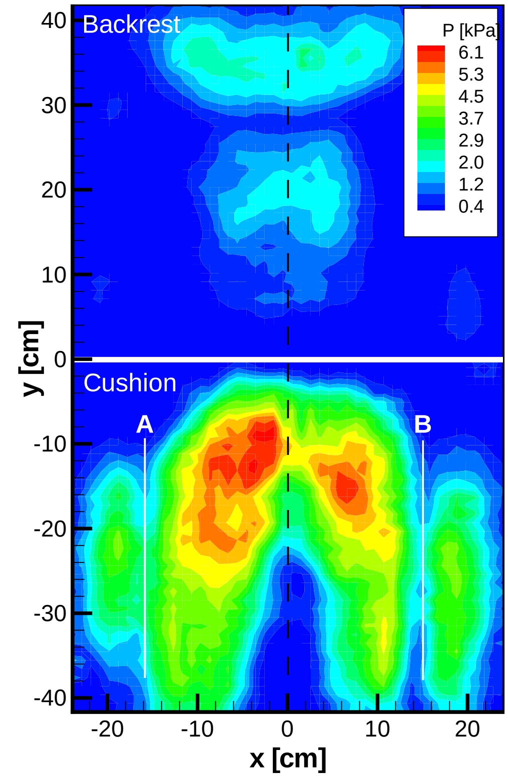

Figure 1: Average pressure distribution on the seat surface

THERMAL RESISTANCE NETWORK

Energy exchange between a driver's body and the automobile seat occurs through a thermal resistance network extending from the driver's skin to the seat surface. The resistance is due to clothing and is expected to change with the applied load.

A series of experiments was devised to measure the effective thermal resistance of some clothing materials as a function of load. Denim was chosen to represent the driver's clothing. Experiments were conducted on 1 mm thick denim samples using an apparatus shown in Figure 2. Thermal resistances were measured by determining the temperature drop across the specimen(s) for preset heat flow rates. The applied load ranged from 1 to 100 kPa. The details of the test rig and experimental procedure can be found in Culham et al. (2002) [1].

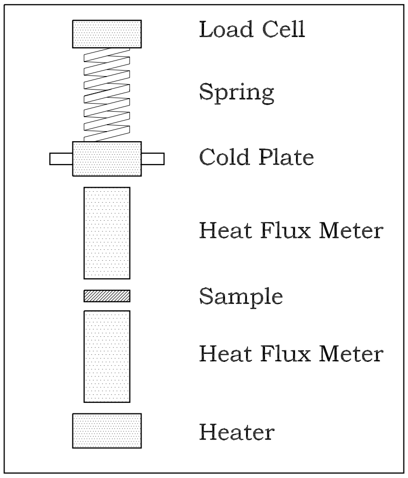

Figure 2: Apparatus for measuring thermal resistances

The experimental data displayed that a linear relationship exists between the thermal resistance and the applied load as given below:

$$R_{Denim} = 10.769 - 0.0145P \qquad (W \cdot K^{-}1) \tag{1}$$

where P is in kPa. As expected, denim resistance decreases with the applied load however, this dependency is very weak. On the other hand, the maximum reduction in the thermal resistance for an average driver's load is less than 1.0%. This implies that the heat transfer in the contact area is almost uniform.

THERMAL MODELING

The vehicle seat under study consists of a heating pad with embedded carbon fibers. The pad is located beneath the leather cover. The heating pad covers only the middle section of the seat cushion and the backrest where maximum contact exists with the driver (Fig. 3). When activated, electric current passes through the carbon fibers and generates heat which is then conducted through the leather cover. The structure of the seat was described in Karimi *et al.* 2002 [5] in detail.

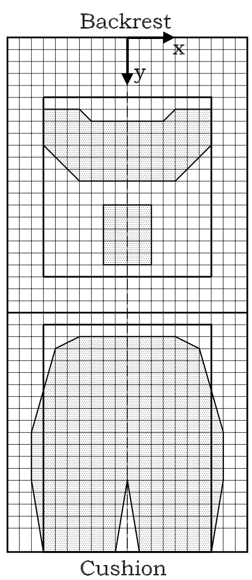

Figure 3: The approximate map of the body/cloth in contact with the seat

A finite volume method was used to simulate the temperature distribution in the seat as a function of time. The general governing equation can be presented as:

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T + S \quad (2)$$

Where the seat local temperature, T, varies with spatial coordinates and time, t. The thermophysical properties k, ρ , and c are the material thermal conductivity, density, and specific heat, respectively. The source term, S, is the heat generation per unit volume for the nodes. The heat generation term is considered to be zero for all nodes except those of the heating pads. A symmetric condition is assumed and the computational domain is limited to the right half of the seat.

Equation 2 is subject to the conduction boundary condition for the areas in contact with the driver. For the uncovered areas, heat exchange between the seat and the ambient air occurs by convection and radiation. The effective local heat transfer coefficient can be defined as [3]:

$$h_{eff} = h_{conv} + h_{rad} = C\left(\frac{T - T_\infty}{L}\right) + \epsilon\sigma(T^2 + T_\infty^2)(T - T_\infty) \quad (3)$$

where T_∞ is the ambient temperature, L is a characteristic length, ϵ is the surface emissivity, and σ is the Stefan-Boltzmann constant. The constant C is 1.42 and 1.32 for horizontal and vertical surfaces, respectively.

Thermal interactions between the seat and the driver's body in contact areas are determined as follows: the contacting body is considered to be made of 3 layers; core, skin, and clothing. The core temperature is considered to be fixed at 37 ^oC during the simulations. A pressure threshold (*e.g.* 0.2 kPa) is defined to identify the contact areas. The contacting regions are then discretized to match the seat surface mesh. An energy balance is written for each control volume to capture variations of local cloth and skin temperatures with time.

RESULTS

Thermal interactions of an average driver with a heated seat are simulated under severe winter conditions. The driver's body and clothing in contact with the seat are divided into several control volumes of different sizes and constant thermophysical properties are assigned to each segment. The driver is assumed to be wearing a denim outfit.

The driver's initial skin and cloth temperatures are considered to be at 34 and 30 ^oC, respectively. The core temperature was considered to be constant at 37^oC during the simulation period. All simulations are performed over a period of 20 minutes when a steady-state condition is approximately reached. A time interval of 10 seconds was chosen in all simulations.

Initial cabin temperature is considered to be at 0^oC. It is also assumed that the seat initially comes to a thermal equilibrium with the ambient air. Although the cabin air temperature is usually changing non-linearly during the warm up period, the air temperature is considered to increase linearly to the comfort level of 22 ^oC over a period of 10 minutes and stays there afterwards. During the simulation a total of 80 W heat is generated in the heating pads which is transferred to the contacting areas, dissipated to the ambient, or accumulated in the seat.

It will be very helpful to compare the heat transfer potentials in the occupied and un-occupied areas. An effective heat transfer coefficient is defined based on the local thermal resistances on the seat surface. The effective heat transfer coefficient is calculated using Eq. 3 for the un-occupied region. For the contacting areas, the effective heat transfer coefficient is obtained based on the experimentally measured thermal resistances. Hence, this represents the effective heat transfer coefficient from the seat surface to the driver's skin.

Variations of the effective heat transfer coefficient on the seat cushion and backrest are shown in Fig. 4 at the end of 20 minutes. Careful examination of this figure indicates that there exists a uniform thermal resistance in the contacting areas. The heat transfer coefficient is estimated at 144 $W{\cdot}K^{-1}{\cdot}m^{-2}$ with a maximum deviation of about 1% due to variation in the local loads. The heat transfer coefficient in the un-occupied region on the other hand, shows a more noticeable variation due to the presence of a temperature gradient on the seat surface. However, the heat transfer coefficient changes from 9 to 11 $W{\cdot}K^{-1}{\cdot}m^{-2}$ in this region.

Figure 5 shows variations of the ambient air, seat surface, clothing, and the occupant's skin temperatures as a function of time. The temperatures related to the cushion side are shown with solid lines and those associated with the backrest are indicated with dashed lines. As mentioned before, the ambient temperature is linearly increased from zero to 22^oC and then levels off at this temperature. The seat surface temperature increases rapidly during the first minutes of simulations. This is due to the significant temperature difference between the seat surface and the contacted clothing. As this thermal driving force is decreased with time, the rate of temperature increase is reduced. The clothing temperature is reduced initially due to the contact with the cold seat however, its temperature starts to recover after about 2 minutes. This is due to the heat generation in the seat which can be felt on the surface. The occupant skin temperature is slightly affected. This is because there is a larger thermal resistance between the seat and the skin and also its thermal capacity is relatively larger than other layers. The slight difference between the temperatures on the cushion and the backrests is due to difference in the coverage area.

Figure 6 shows simulated temperature distributions on the seat surface after 20 minutes. Figures 6-a, b illustrate the temperature profiles for the un-occupied seat. As indicated, the surface temperature in the heated area is increased to about 31 ^oC. The low thermal conductivity of the seat materials results in a uniform temperature and only a very narrow region of the non-heated areas are affected. On the other hand, the non-heated regions are warmed up slowly by natural convection as the ambient air temperature is increased.

With the seat occupied, heat is rapidly exchanged between the clothing, initially at high temperature, and

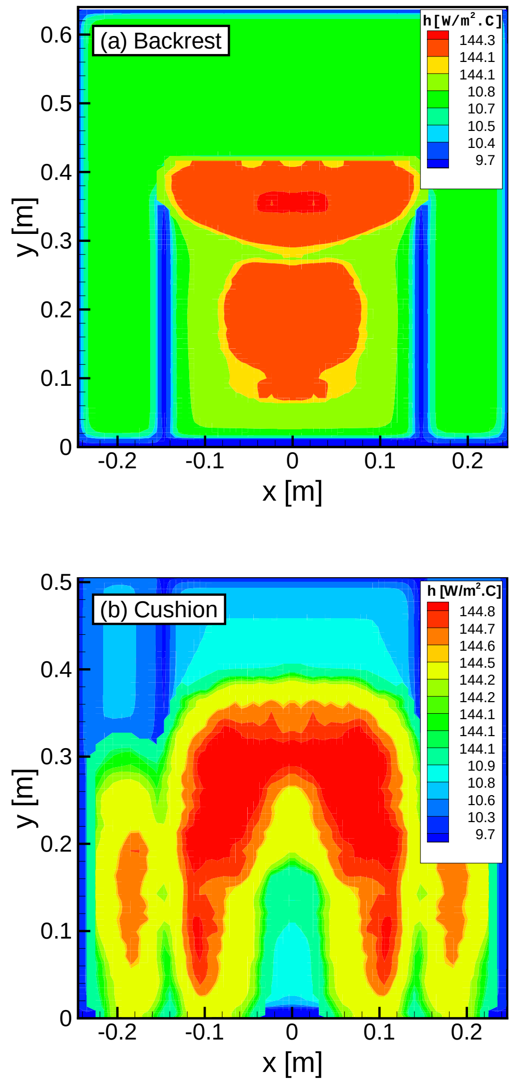

Figure 4: Effective heat transfer coefficient on the occupied seat

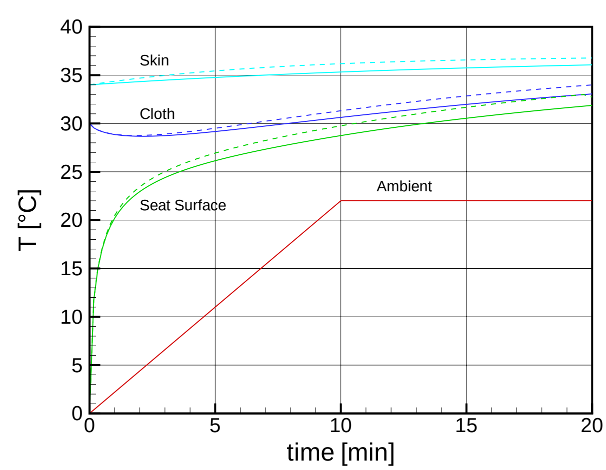

Figure 5: Time variations of temperatures in the contact areas

the seat. The rate of heat transfer is very high at the beginning and drops gradually as the temperature differences reduce. Comparison of temperature profiles for the occupied and non-occupied seats clearly shows that a higher temperature prevails in the contacted areas. This is due to the heat generation in the driver's body and is obvious for non-heated areas in Fig. 6-c.

Steady-state temperature profiles for the driver clothing and skin are shown in Fig. 7. It is seen that the cloth temperature increases about 3^oC in heated areas and drops about the same level in un-heated areas.

Although a temperature difference of about 6^oC exists between cloth temperatures in different areas (heated and un-heated), the driver's skin temperature is almost uniform in all contacted areas independent of the seat location. This is due to the presence of a larger thermal resistance through which heat is transferred and a larger skin thermal capacity as previously pointed out.

Again it is seen that there is no significant difference in temperature distributions in the contacted areas. On the other hand, the effect of exerted load on the seat temperature in the contacted areas is negligible.

SUMMARY AND CONCLUSIONS

A transient physical model is developed to simulate the thermal interactions between an automobile driver, the cabin environment, and a heated seat. The model uses the measured load distribution in the driver-seat contacting areas to develop a thermal resistance network and to determine the rate of heat transfer. From the experimental measurements and the simulation results it can be concluded that the effect of driver's load on the thermal resistances in the driver-seat contact areas is insignificant. This causes a relatively uniform temperature to be developed on the driver's cloth and skin in contacted areas. On the other hand, designing a non-uniform heating pattern on the seat seems to be undesirable. Further experimental data including human subjects are required to verify these findings.

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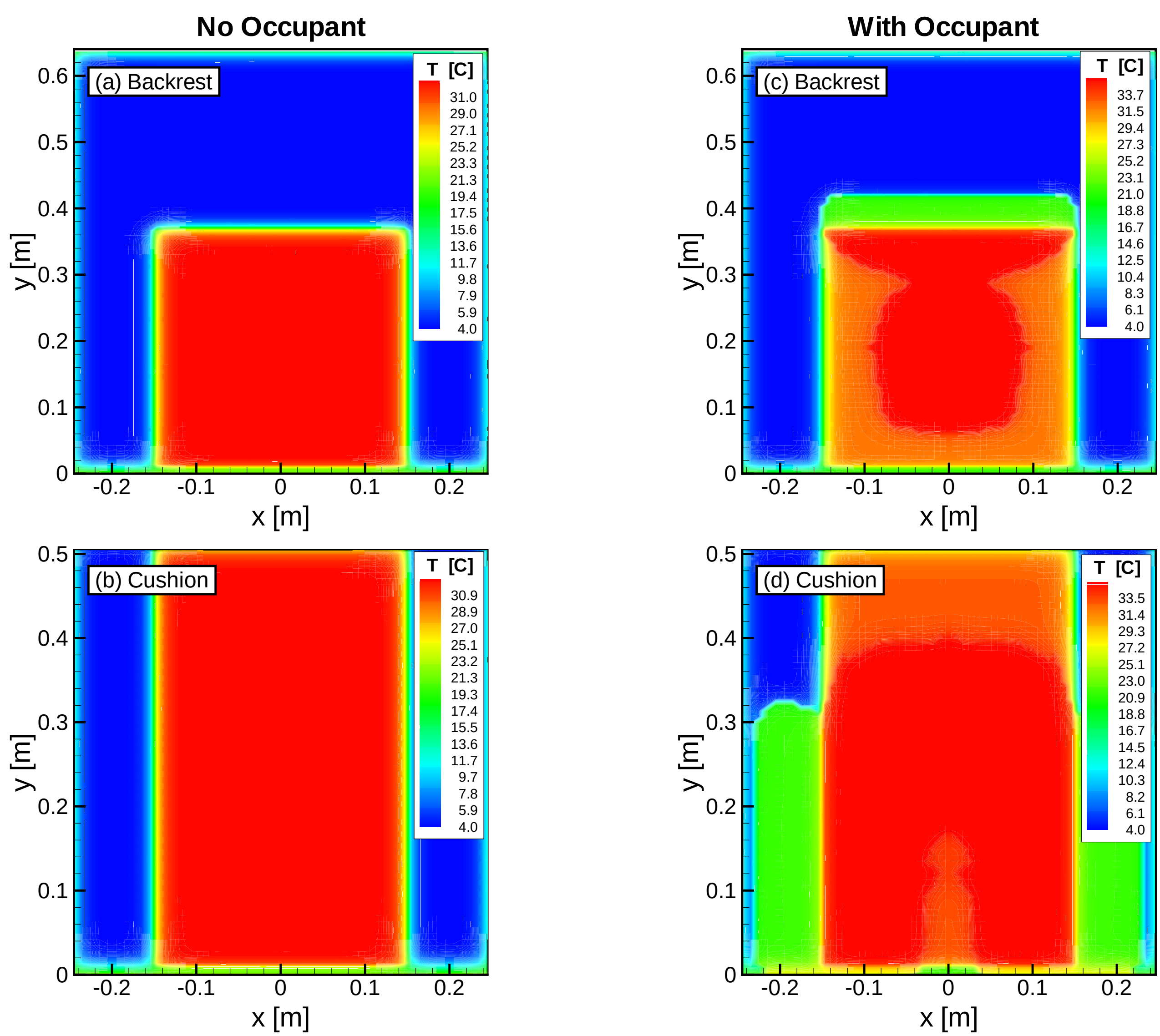

Figure 6: Temperature distribution on the seat surface after 20 minutes: (a, b) no occupant and (c, d) occupied seat.

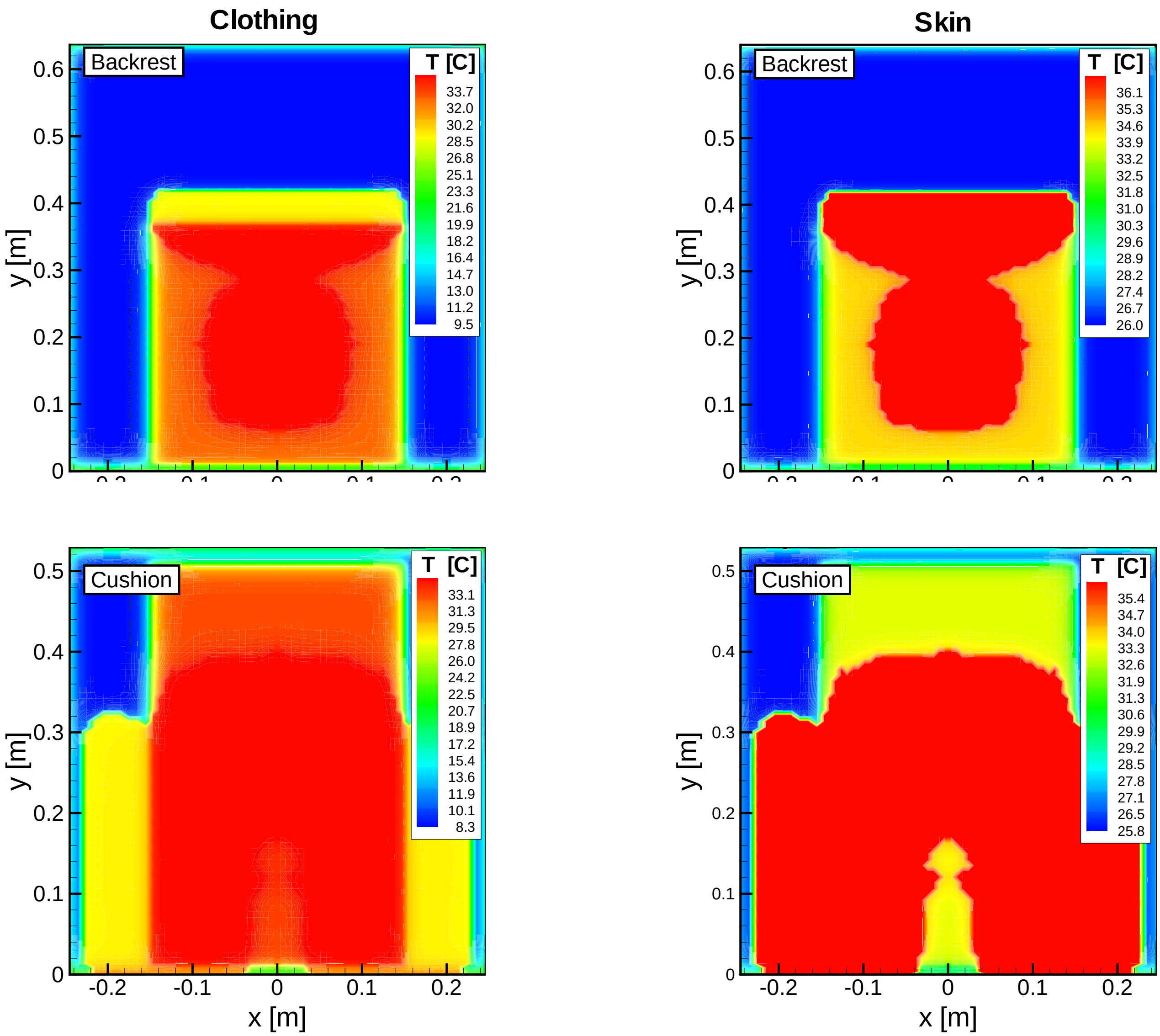

Figure 7: Temperature distributions after 20 minutes: (a, b) contacting cloth and (c, d) contacting skin.