

Predicting Temperature Limit Values for Cold Touchable Surfaces

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Emiel A. den Hartog

TNO Defense, Security and Safety

Business Unit Human Factors

Dept. of Human Performance

P.O. Box 23

3769 ZG, Soesterberg

THE NETHERLANDS

Tel: +31 346 356 288

Fax: +31 346 353 977

Email: emiel.denhartog@tno.nl

ABSTRACT

During some occupational activities, workers have to handle objects or tools in cold environments. In other circumstances, contact between the hand and the cold surface might be accidental (e.g., when a worker touches a cold surface, a cooler, etc). In both cases, contact between the hands and the cold material can induce discomfort, pain or frostbite, and exposure to cold may negatively influence the dexterity and the manual sensitivity of the subject [1]. Four years ago the EU started to finance a research project to determine the maximum duration of touching and gripping materials in the cold.

In four different European labs, six male and six female students participated in the study. All subjects touched 10cm x 10cm blocks of different materials: wood, nylon, steel and aluminium. The 5 materials chosen were representative of a wide range of thermal properties that are relevant to cold surfaces. The subjects were asked to touch with their index finger the materials maintained at temperatures ranging between -40°C and -5°C . Thermocouples were placed on the back of the hand and on the touching surface of the finger. The subjects scored their subjective ratings on scales of pain and numbness with 5 levels (0 to 4; from total absence to intolerable level).

From all the experiments, an extensive data set was collected on cooling curves of the fingers touching the mentioned cold materials. From this data set general safety limits could be derived for touching cold surfaces of various materials. Additional modelling allowed extending the duration limits beyond the range of the data. Furthermore, recent developments in the modelling showed that the actual limits are leaning on the safe side, due to the measurement technique that has been used.

In conclusion, touching experiments were conducted to determine the maximum allowable tolerable exposure duration at different temperatures and for different materials. This duration varies inversely as a function of the material constants and linearly as a function of the temperature of the material. Modelling this problem allows the development of exposure limits outside the experimental range and to improve the validity of the experimental limits.

1.0 INTRODUCTION

In cold environments it is unavoidable that materials are touched. People may have to handle tools or move objects around. While touching materials in the cold, cooling of the skin will occur due to the temperature difference between the skin and the surface of the material. In conditions below 0°C, this may lead to severe discomfort, pain, frostnip or even frostbite. In a EU-funded research project the limits of exposure to contact cooling have been explored, with the aim of setting standards for touching and handling materials. In this project a large number of experiments have been performed, divided into two parts. The first part dealt with the risk of short term, accidental, touching of cold materials. The second part deals with the gripping and handling of materials, and thus, with longer exposures. However, as it is impossible to perform experiments with all types of materials for a large range of temperatures, and because for some combinations of materials and temperatures the risk of skin damage is too high, modelling was incorporated in the project. This study was aimed at producing an analytical model of skin cooling, in order to allow intra- and extrapolation of skin cooling in relation to material properties and temperature, beyond the conditions for which actual data were collected. In this paper the work on the development of models to simulate the touch experiments will be described.

2.0 EXISTING MODELS

In the literature we identified only two groups that have described models of contact cooling with solid materials. A study by Havenith et al. [1], aimed at producing an empirical description of the data from experiments in which subjects gripped cold bars of different materials. These experiments were performed on aluminium, steel, nylon and wood at -10°C, 0°C and +10°C. From this study, Lotens [2] developed an analytical model to simulate the cooling of the hand palm during the grip experiments. The second group, Chen et al. [3] have published experimental data on the touching of materials with the fingertip. They also published empirical models of the experimental data that consisted of functions with 2 exponentials. Within the ColdSurf-project a model was produced, consisting of a finite element model, which was used to show that such a model could fit individual cooling curves (Den Hartog & Havenith [4]). The present paper will focus on the translation of those model results into more general data that can be used to write guidelines and standards for cold contact. In figure 1 the model is shown. The details have been described before [4].

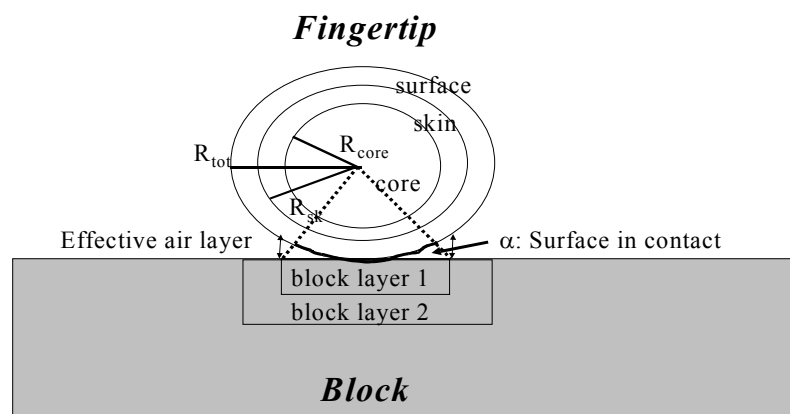


Figure 1: Schematic presentation of the model to simulate contact cooling of the fingertip on a cold block. The finger is represented as a cylindrically shaped object. The grey square represents (part of the) cold block. The finger is divided into three coaxial segments, the block into two small surface segments. The relevant model parameters are: R_{tot} = finger thickness; R_{skin}/R_{tot} = Relative thickness of the outer finger layer; R_{sf}/R_{tot} = Relative thickness of the second finger layer; α = contact surface area of the finger; $dblock1$ and $dblock2$ = the thicknesses of the two block layers.

3.0 EXPERIMENTS & MODEL RESULTS

The validation of the model could be performed using the experimental data of the touch experiments that have been performed in the “ColdSurf” EU project. The experimental set-up of the touch experiments has been described extensively in the respective reports on this subject [5]. Therefore, only some essential details will be described here. The index finger was placed on a 10 cm x 10 cm block. In the middle of the palmar side of the fingertip (index finger, non-dominant hand) a small thermocouple was placed (0.1 mm diameter), so that it was within the contact area of the finger and the block. The experiments were performed on aluminium, steel, nylon and wooden blocks at temperatures ranging from –40°C (wood) to +5°C. In total more than 1734 experiments were carried out with human subjects at four different laboratories. In our previous paper it has been shown that the presented model can be used to fit individual cooling curves [4].

4.0 SETTING LIMITS – PREDICTION OF 25TH-PERCENTILE

This research project on touching and gripping cold surfaces has been initiated to develop safety limits for cold contacts. Therefore, the modelling was aimed at setting safety limits. As was concluded before [4], it was possible to fit individual curves by adapting the model parameters. But for producing safety limits a general model is needed, preferably for all possible conditions, which can predict the behaviour of the lower 25th percentile of the population. Two options were possible: From this point two pathways can be followed:

Option 1: Fitting all individual curves and trying to find the lower 25th percentile of each individual parameter. This may lead to wrong results since the parameters may be dependent to some extent.

Option 2: Trying to fit the lower 25th percentile of the curves, i.e. the curves are not fitted individually, but the whole group of curves is used.

As the outcome of using option 1 is uncertain, option 2 was chosen. After studying the effects of the different parameters it seemed that only the first parameter (R_{skin}/R_{tot}) needed to be changed for different materials. The size of this parameter was dependent on the contact coefficient. The contact coefficient, or contact factor (F_c) is the square root of the product of the material conductivity (λ), the density (ρ) and the specific heat (c), or: $F_c = \sqrt{\lambda\rho c}$. The values for F_c are approximately: 21200 (Aluminium), 7270 (Steel), 780 (Nylon) and 520 (Wood).

The following equation for this parameter provided the best results over all conditions.

$$R_{skin}/R_{tot} = -0.025 \cdot \ln(F_c) + 1.15$$

This equation was used to set the model parameter and compute the cooling curves that were measured within the ColdSurf project. In figures 2 to 5 the results of the model were compared to the experimental results. The results seem to behave in a way that is similar to the 25th percentile of the data. It is a qualitative indication, although there has been no extra analysis to compute exactly the 25th percentile equations. But, a result of the ColdSurf project was an empirical equation of the 25th percentile of the data. The equations for the time to reach 7°C and 0°C are:

$$T(7) = (454.617 / F_c^{1.80048}) * \exp(0.120244 * F_c^{0.466832} * T_s)$$

$$T(0) = (980.466 / F_c^{1.02875}) * \exp(0.210394 * T_s)$$

In which F_c is the contact coefficient and T_s the material surface temperature [5].

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These equations can be compared to the model results. The difference is that the empirical model is based on the database values from the cooling curves. At each temperature and material that was available the 25th percentile to reach 0°C (or 7°C) was taken as input for the model. With the model we looked for the 25th percentile of lowest curves. The comparison between the model and the empirical data, is shown in figures 6 (for 7°C limit) and 7 (for 0°C limit – i.e. frostnip).

Figure 2 to 5: Comparison of the model to the measured data of finger contact temperature, for four materials at different temperatures, $\beta = \ln[\sqrt{(\lambda \cdot \rho \cdot c)}]$. The values for β are: 10 (Al), 8.9 (St), 6.7(Ny) and 6.3 (Wd). The starting skin temperature was set at 20°C, except for Nylon at -30°C where it was adjusted to the data. The data were collected at different partners of the ColdSurf project: TNO (NL), FIOH / ORIOH (Fin), NIWL (Swe) and Loughborough University (UK).

Fig.2: Aluminum, 0°C

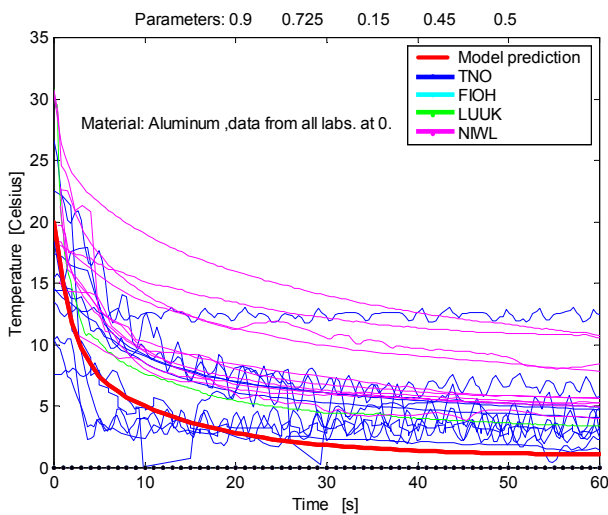


Fig. 3: Steel, 0°C

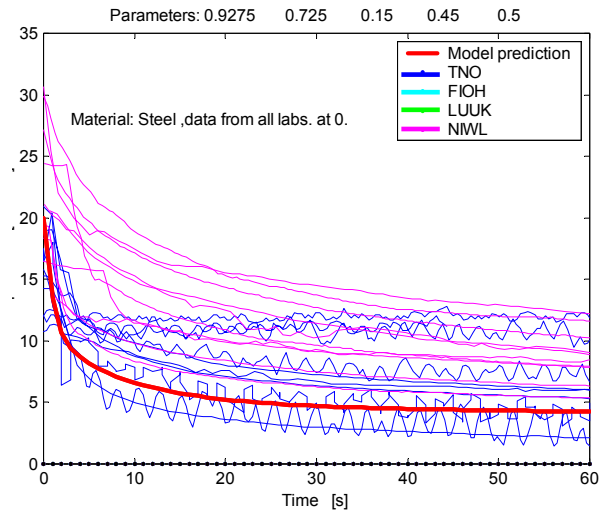


Fig. 4: Nylon, -30°C

Starting skin temperature adjusted to the data

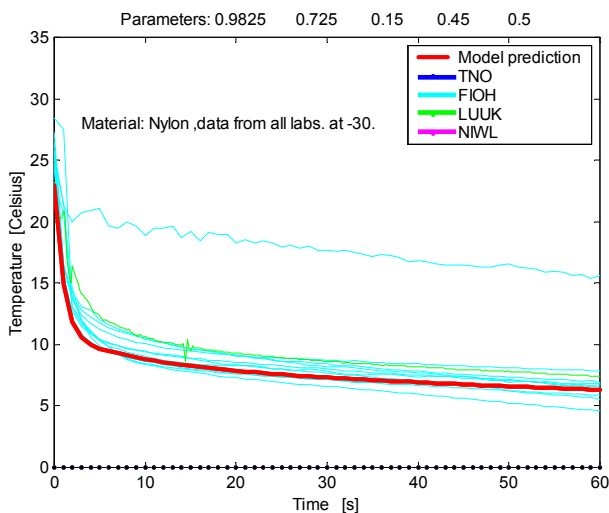
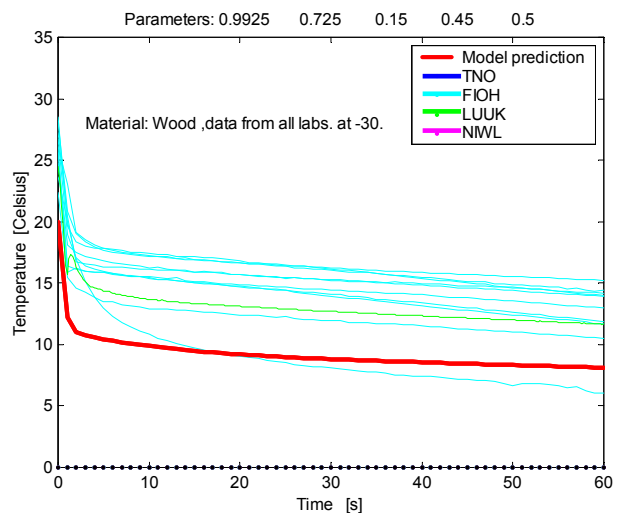


Fig.5: Wood, -10°C



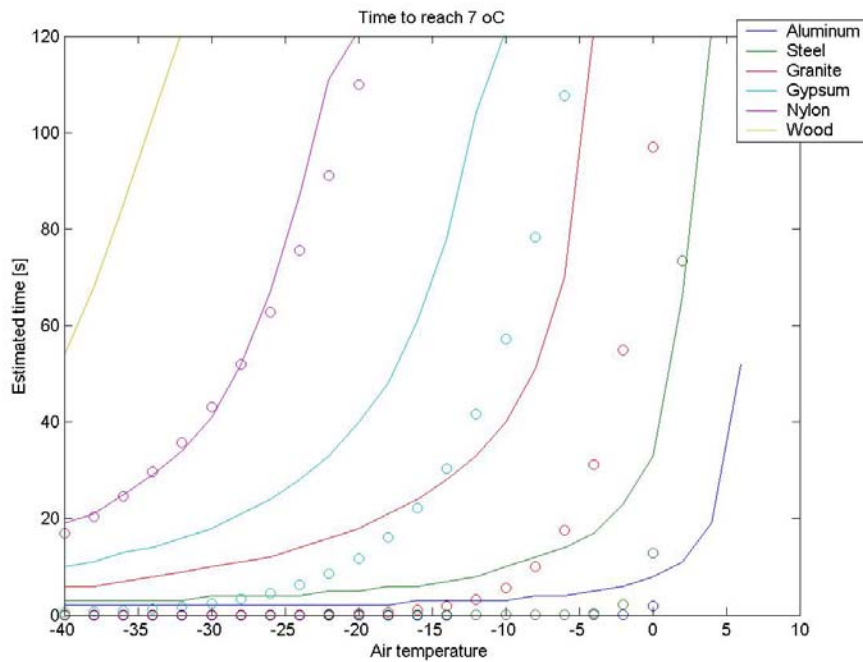


Figure 6: Limit criterion to reach a finger skin temperature of 7°C, derived from the model. A starting skin temperature of 20°C was assumed. The colours indicate the different materials in the legend.

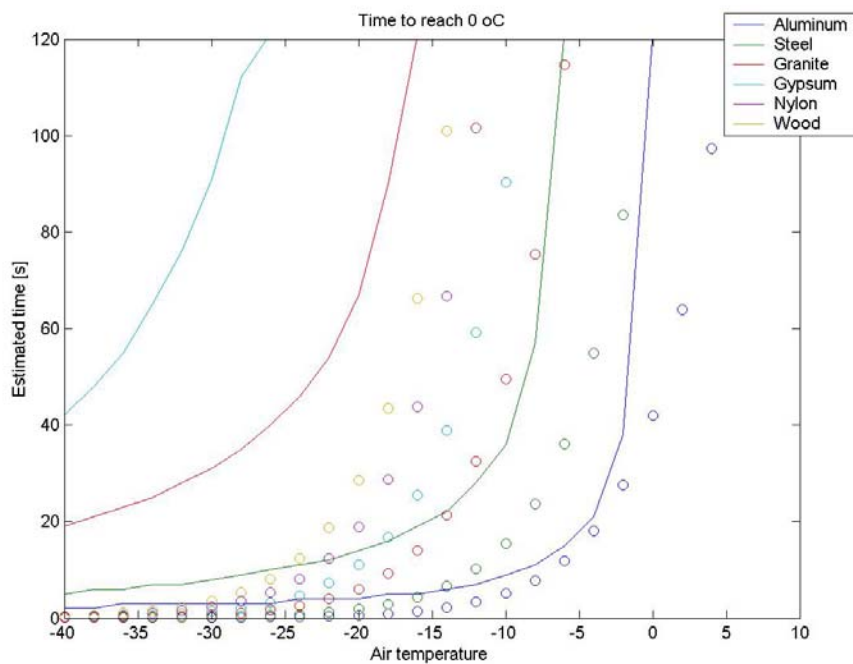


Figure 7: Limit criterion to reach a finger skin temperature of 0°C, derived from the model. A starting skin temperature of 20°C was assumed. The colours indicate the different materials in the legend.

5.0 DISCUSSION & CONCLUSIONS

Using an analytical model we were able to simulate cooling curves for a large range of individuals at different temperatures and for different materials. The advantage of an analytical model is that it can lead to the identification of parameters that are important in the process that it describes, and thus, to a better understanding of the process (i.e. contact cooling). In this way the reliability of extrapolations can be largely improved. Unfortunately, we have not (yet) been able to identify a single set of parameter values to create a unique model for which all conditions can be simulated. For an optimal fit of the simulation to the cooling curves, the parameters (especially $R_{\text{skin}}/R_{\text{tot}}$) had to be adapted to each condition (material and temperature). Still, this method served as an aid to describe the most important features of contact cooling for different temperatures and different materials, without actually measuring all of them. From this point it did seem possible to use this model to generate safety margins for a variety of materials at a large range of temperatures. This was achieved by using an ‘average’ model, which fitted the fastest cooling rates that were measured. Only the first parameter, the size of the outer component of the finger, needed to be adapted for different materials. A linear relation between the natural logarithm (ln) of the contact coefficient (Fc) and the size of this layer was used. Currently the selected parameter set was selected “by eye”. This means that no objective criterion was used to use this set in stead of a (slightly) different one, other than looking at the curves and the fit and subjectively selecting a parameter set. These parameter values may be used to predict cooling curves and set safety limits at different temperatures and materials, as the times to reach 7°C or 0°C can be computed for any material at any temperature. These temperatures correspond to the occurrence of numbness and frostnip respectively. Also the effect of starting skin temperatures can be studied. In figure 6 and 7, examples of safety limits derived from the model are shown. The limit criteria are shown not only for the used materials, but also for gypsum and granite. The model results were compared to the data that have been suggested for the standard [5]. The standard seems to be overprotective if the model is to be considered valid. The model results as presented here can give new input to the values in the standard, provided that the model is further improved and validated. The results presented here are one step further compared to the modelling results that have been published earlier [4], as these data suggest the model may not only be used to fit single curves, but can also predict the 25th responses of all subjects.

In the future, research can be directed to improving the model and identifying the reasons of the required model parameter variations. Probably, the results are related to the actual temperature measurement method. The temperature was measured by thermocouple, which influences the local exchange of heat between finger and block. Initial model calculations seem to show that if the thermocouple is added to the model, it may result in a more stable configuration of the model and, therefore, in more reliable predictions of the limit values. This would improve the reliability of the extrapolated curves that have been used as input data to develop a standard for touching cold surfaces. There seem to be some differences between the equation based on empirical data and this model. This analytical model could provide a better understanding of the local phenomena of cold materials contact. When the effects of the thermocouples are considered in the model it may result to optimal guidelines for touching cold surfaces. In this way the model can be used to set limits and give guidelines to prevent frostnip while touching cold materials.

6.0 REFERENCES

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