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Thermal simulation of a dinghy sailor

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Abstract

This paper describes the development of a model to simulate a dinghy sailors’ body temperature during a sailing match. This simulation has been developed as part of the master thesis by the author: “Thermal optimization of competitive sailing gear”. A literature study is done to define the human body heat balance and thermal comfort. Next a basic heat balance model was developed and simulated in MatLab Simulink. A field test was used to validate an elaborated model and recommendations are given for future work on this subject.

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1. Introduction

In a race, sailors experience differences in thermal comfort, mainly caused by the changing conditions they face on the different courses they sail; for most Olympic classes these are predominantly upwind and downwind legs. Each course requires another type of activity and influences the environmental conditions to which the sailor is exposed (i.e. apparent wind speed).

Many (even top-ranked) sailors struggle with finding the right suit (combination) for a certain day of sailing. The effect of changing conditions due to various course on thermal comfort is widely known and generally accepted as being ‘part of the sport’. This is even accepted while realizing that the thermal state of the body, and the athlete’s perception thereof play an important role in their performance.

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An overall body temperature of about 38.5 °C and a muscle temperature of 39 °C or higher are optimal for sports performance; a higher temperature increases the blood oxygen uptake level in the muscles, nerve signaling speed and overall metabolic rate, Astrand and Rodahl (1986). However, it is generally believed that at body temperatures over 39.5 °C performance starts to degrade, Lotens (1993).

The perception of the thermal comfort state of the body is mainly based on the sensation of heat exchange with the environment; cooling or heating the body, Brown and Gillespie (1986).

The goal of this research is to develop a quantitative method to assess the needs of the sailors, the influence of environmental factors and clothing configurations. The research is part of the master thesis of the author, which also included the design of sailing gear, developed using the described model. The design is focused on single-handed dinghy sailors (i.e. Laser), as they face the most extreme conditions and exercise levels.

A literature study is done to define the human body heat balance and thermal comfort. Next a basic heat balance model was developed and simulated in MatLab Simulink. A field test was used to validate an elaborated model.

2. Heat balance analysis

Of the energy converted in the body a part is used to move the body: ‘work’, the rest is released as heat. The percentage of metabolic power used to move the body is described in the Gross Efficiency (GE), Hettinga, Koning et al. (2007). In a thermo-neutral environment, an athlete operates at a GE of about 20%, Hettinga, Koning et al. (2007), this means the rest of the heat is dissipated in other ways than work.

During intensive sports activities, the body attempts to maintain an stable core temperature by adjusting its heat exchange with the environment. The heat balance of a human body and its environment can be calculated by the sum of metabolic heat production, work, heat storage and modes of heat loss, NEN (2004).

\[
M-W=K+C+R+E+S \tag{1}
\]

Where:
- \(M\) Metabolic rate [W]
- \(W\) Effective work [W]
- \(K\) Conduction [W]
- \(C\) Convective heat exchange [W]
- \(E\) Evaporative heat exchange [W]
- \(R\) Radiative heat exchange [W]
- \(S\) Surplus (body heat storage) [W]

All factors in this equation but work represent the sum of their respective heat exchanges. Conductive heat transfer to the environment can be neglected for a dinghy sailor, because the thermal conductivity of air is very low and only small, good insulated parts of the body are in contact with the boat (because of hiking pads and padding). Leaving a more simplified heat balance equation, where \(M_{\text{heat}}\) represents the body heat production:

\[
M_{\text{heat}}=C+R+E+S \tag{2}
\]

1.1. Heat transfer models

The Metabolic Rate is calculated from data obtained from a training session of Laser sailors. During the training, GPS position, Heart Rate (HR) and Energy use are logged over time for a group of 6 sailors. According to Castagna and Brisswalter (2007), Heart Rate is a good indication for the exercise intensity of dinghy sailors. Linking the HR measurements to course, derived from the GPS track, shows the difference between upwind and downwind sailing. Convective heat exchange is calculated according to NEN (2004). Seating position of the sailor at different courses is taken into account as it affects the area available for Radiative, Convective and Evaporative heat exchange, Kurazumi, Yoshihito et al. (2008). Radiative heat exchange is dominated by the incoming solar radiation and is modeled using the COMFA method by Brown and Gillespie (1986). Evaporative heat loss is modeled using the Lewis relation described by Awbi (1991). Finally, the surplus heat flow determines changes in body temperature. When more heat is produced in the body than dissipated to the environment, the body core temperature will rise and vice versa.
3. Model development

The general cross section of the body shows the schematic heat flow; heat is generated in the body mass by muscle movements and other processes. It’s then conducted through the skin and a layer of clothing to the clothing surface. From the surface, heat is dissipated through Evaporation, Radiation and Convection to the environment.

The heat flow can be expressed in a thermal network, Strijk (2008), in which all modes of heat transfer are included. Using the R,C network method provides an overview of the heat flow and involved factors. Following the analogy with an electrical network, the basic electrical calculations for networks in series and parallel can be used as well. In the R,C network, clothing layers are described as resistors, metabolic heat power as a power source and thermal masses (like the body) as a capacitor. The flow direction is from body core to environment (left to right), when the sailor is warmer than his environment.

Sailor and clothing are described in terms of mass, surface area and material properties such as density and thermal conductivity. Coefficients are added to describe the seating position (influencing the exposed area to spraywater and convection) and the sailed course relative to the wind direction. Initially, the model describes a Laser sailor of 75 kg/m80. Adjusting these variables in the model allows for creating individual profiles and calculations. Various scenarios were used to evaluate the effect of course changes during sailing. It’s important to apply these variables in the model because the varying level of heat exchange with the environment is at the core of the design challenge in the clothing design project. The scenario contains course-dependent variables; relative wind speed, surface wetness of the sailors’ garment (due to spray water), surface area exposed to convection and the exercise intensity for three activities; resting, sailing upwind and sailing downwind. Factors correcting for the exposed areas for radiation and convection show small differences between the legs and are not taken into account.

The R,C network is detailed further by defining various body parts and layers of apparel using Simulink software. The model allows for adding various pieces of equipment and clothing layers to the thermal network. In this way, the effect of different clothing combinations can be described and simulated. Special (adaptive) clothing properties may be constructed using the same approach. Figure 3 describes a thermal network of a sailor wearing a 3/2 mm...
wetsuit, buoyancy aid and hiking pant.

Figure 3. R,C network of a laser sailor wearing wetsuit, buoyancy aid (B.A.) and hiking pant

4. Validation; Experimental Setup and results

During a Laser sail training day Core Temperature, Heart Rate, GPS position and video are logged for 6 Laser sailors training at Scheveningen. Core Temperature was measured for one sailor using a CorTemp® Physiological Monitoring System and Heart Rate was measured using a Polar Heart Rate monitor, weather data was retrieved from observations, KNMI (2011). Weather observations, HR, video and GPS are used to reconstruct the scenario and ambient conditions of the training in the simulation model and to calculate the metabolic heat production. Large deviations in body core temperature are filtered from the logged data, as these are likely to be caused by communication errors between logger and temperature sensor. Measured and simulated core temperatures are then plotted against each other in a T/T plot, on which a linear trend line is drawn and R² calculated. Plots are made both for the complete training, and for the consecutively sailed courses separately.

The training consisted of upwind and downwind practice runs with short resting periods in between, as shown in Table 1. The weather conditions (averaged) were: ambient temperature of 13.3°C, wind 11 m/s, solar radiation 169 W/m². Linking the GPS track to the HR measurements shows upwind sailing is in the range of 70-90% of max. HR and downwind is in the range of 80-90% of max. HR. On average, the Metabolic Rate upwind is found to be 1236 W, downwind 1084 W and in rest 788 W. Note that the Metabolic Rate does not differ much between up- or downwind courses, but the range of exercise intensity is twice as large for upwind sailing. Core temperature gradually rose from 37.2 °C to 39.2°C up to resting moment 2. During resting moment 2 and the last downwind leg, the core temperature lowered to 38.9°C.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Upwind 1</th>
<th>Downwind 1</th>
<th>Rest 1</th>
<th>Upwind 2-1</th>
<th>Upwind 2-2</th>
<th>Rest 2</th>
<th>Downwind 2</th>
<th>Total training</th>
</tr>
</thead>
<tbody>
<tr>
<td>time [min.]</td>
<td>13</td>
<td>8</td>
<td>3</td>
<td>13</td>
<td>19</td>
<td>5</td>
<td>8</td>
<td>69</td>
</tr>
<tr>
<td>R²</td>
<td>0.93</td>
<td>0.90</td>
<td>0.95</td>
<td>0.82</td>
<td>0.77</td>
<td>0.20</td>
<td>0.5</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Table 1 Training activities, time and R²

Figure 4 shows the simulated vs. the measured core temperature of the Laser sailor for the complete training session and a linear trend line, for which an R² of 0.88 is calculated. Deviations are largest for higher body
temperatures (around 39°C). The simulation quality is evaluated more in detail by plotting and calculating $R^2$ for the training activities separately. Like figure 5 which shows data of the first upwind leg. Resulting $R^2$ values are included in Table 1.

![Figure 4. T/T plot and $R^2$ of the complete training, including a 1:1 line (dashed)](image)

![Figure 5 T/T plot of Upwind Leg 1, including a 1:1 line (dashed)](image)

5. Conclusion

Plots and data analysis show high $R^2$ between the simulated and measured data for the first part of the training. The coefficients of determination for the last two activities are very low. Slowly rising core temperatures indicate that the sailor has done a reasonable clothing selection, but improvements can be made to mitigate the difference in heating rate between upwind and downwind. In general, the proposed method is found to be a helpful tool in assessing a sailor’s heat balance, although it is very difficult to accurately model a human, especially in an extreme environment like a sailing dinghy.
6. Discussion

Heart rates were found not to be an absolute measure of metabolic rates. For example, when a sailor has boosted his HR to maximum for rounding the upwind mark, it doesn’t mean he used the same amount of power on the first part of the following downwind leg. For this reason, averages were found and used in all simulation runs.

Deviations in temperature between model and measurements over the last part of the training may be caused by an elevated body temperature. Possibly, heat exchange with the environment is different than expected at a higher temperature. Another cause of error may be a change in conditions which has been overlooked when creating the simulation scenario, a change of clothing for example. Modelling a sailor’s heat flow was found to be very useful for evaluating clothing designs. Next to the core temperature, the model provides insight in the experienced comfort through the rate of cooling or heating of the body. Using the model, a set of sailing gear was designed aimed at optimal thermal comfort over a complete sailing match.

7. Recommendations

The model was validated using data gathered on two days of sail training. The reliability of the validation process can be improved when data of more experiments with varying sailors, garment and environmental conditions are available. In general, the model can be improved by further refining the input data; weather conditions, boat speeds, race strategies and clothing characteristics can be described in more detail. Further research should be performed to determine the exercise levels and energy cost of certain activities, weather conditions and actions during a sailing match. Averaging metabolic rate for a certain activity simplifies the use of the model and the composition of sailing scenarios, but lowers the accuracy. A higher accuracy can be reached when the metabolic rate is modelled in more detail.

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9. References