Hypothermia Prevention during the Royal Marriage Party in the Amsterdam Arena Stadium

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Abstract

Shortly before the Royal Marriage Party, on the occasion of the wedding of His Royal Highness Prince Willem Alexander and Maxima Zorreguita, took place in the Amsterdam Arena stadium, the organization realized that the audience might be exposed to cold for a considerable period and that hypothermia might occur. Therefore, the risk for hypothermia was assessed and the effect of counter-measures was calculated using thermal models. The models showed that it was not effective to place heaters in the stadium, but that reducing the ventilation rate was effective. Beer is known to enhance body cooling and was therefore prohibited during extreme cold. An entertainer tried to stimulate the audience to move in order to generate extra heat. Each visitor received a clothing recommendation, which was followed very well.

During the party, the ambient temperature turned out to be exceptionally high, and no problems occurred. Temperature and humidity measurements in the stadium during the party showed that the model calculations were close to the real values.

Introduction

On February 2nd 2002 the Royal Marriage between His Royal Highness Prince Willem Alexander and Maxima Zorreguita took place in Amsterdam. The evening before, a party was planned in the Amsterdam Arena for which 50 thousand guests were invited. The Amsterdam Arena is a large soccer stadium covered by a roof, the home stadium of Ajax Amsterdam (see Fig. 1). With the roof closed, there is still a total opening of approximately 160 m² in the roof.

The guests were invited by the city and village boards in The Netherlands and were expected to consist of a representative part of the Dutch population.

Since February 1st can be rather cold in The Netherlands (about 95% of the ambient temperatures are less than 10°C) and wet (rain in 57% of the days over the last 100 years) and since the temperature in the stadium is only slightly higher than the outdoor temperature, the organization feared that hypothermia might occur during the party. The guests were allowed to enter the stadium at 17.00 hours and the party would end at about 22.00 hours. This five-hour exposure, combined with the suspicion that the guests might be underdressed, made that the organization committee desired a risk analysis and an analysis of possible measures to prevent hypothermia. This analysis is described in this paper, as well as the evaluation of the actual circumstances during the party.

Methods

Climatic assessment

The effect of ambient temperature and humidity on the temperature within the Arena (air volume 1 Mm³) was calculated using AIDA (Liddament, 1989) and ESP-r (ESP-r, 1990). AIDA is a ventilation model for the calculation of air change rates in single zone enclosures. The calculation is based on the iterative balancing of the flow equation. The model takes into account pressure differences due to wind and temperature differences (stack pressure) and the location and size of the openings. The influence of adjacent buildings on the pressure distribution around the stadium, expressed by the wind pressure coefficient, was estimated using the Cp-generator (Knoll, 1995). The Cp-generator is a computer model for prediction of wind pressure coefficients on facades and roofs, based on
fits of measured data, including wind shielding by obstacles and terrain roughness.

Using the data from the ventilation model, the temperature in the stadium was calculated using ESP-r. ESP-r is a transient energy simulation system for modeling the energy and mass flows within combined building and plant systems. The ESP-r approach aims to represent all relevant phenomena, and to process these phenomena simultaneously so that the inter-relationships are preserved. Essentially, this is achieved by establishing sets of conservation equations for different spatial regions and arranging for the integration of these equations over time. The discretisation of the differential equations that describe the heat and mass transfer is done by an implicit method. In this way the method is numerical stable (Crank-Nicolson scheme). The experienced user may use a time step controller in order to reduce the time-step value until the difference in the control variable for the current time-step and previous time-step is within a user-specified value.

The energy and mass flows are tracked—throughout a simulation—as they evolve under the influence of climatic boundary conditions, occupancy effects inside the building, constraints imposed by any control action and by the potentially time-dependent inter-volume links (representing for example damper, valve, window or door movement). The system is currently used for education and research at universities and research centers in over 20 countries worldwide.

For the calculations that need to be done for this exercise, it was not necessary to make the input model fit for every design detail. The Arena geometry was therefore simplified to a level that made it possible to calculate the energy flows in the stadium with acceptable accuracy. The zones that where distinguished are the stadium itself, divided in three layers as far as the galleries are concerned and the spaces behind the galleries. The construction of the galleries, the roof and the floor was put to the model with their respective dimensions and physical properties. Transparent or opaque surfaces are dealt with and also the number of people in the stadium is taken into account. The airflows between the different zones were taken from the calculations with AIDA. Meteorological data were used from the Dutch meteorological office.

Assessment of hypothermia risk

The impact of climate, clothing and metabolism on body cooling was assessed using the Duration of Limited Exposure (DLE) values of the IREQ model (ISO TR11079, 1993) and the output of the THDYN model (Lotens, 1993). Different scenarios were processed in which the ambient temperature was varied. When the metabolism, needed to counteract body cooling, exceeded the maximum that can be produced in a sitting and standing posture for a certain amount of time, it was assumed that body core cooling would occur. The DLE is based on maximal discomfort within 8 hours of work for the industry. At maximal discomfort the hypothermia risk is considerable, especially for people that have a reduced shivering response. A reduced shivering response can be the result of aging (Andersen et al., 1996), or alcohol consumption (Granberg, 1991). Also, paraplegics were considered to be at risk due to their reduced ac-
tive muscle mass. It was assumed that small, slim persons were at a disadvantage, since their surface area to mass ratio is relatively large.

Assessment of the effect of preventive measures

The effect of the following preventive measures was assessed:

a. Additional heating within the building

Using the AIDA-model and the ESP-r-model, calculations have been made on the effect of installing two heaters of 1.2 MW each in the stadium. These heaters were supposed to start a few days prior to the party and stop shortly before the public entered the stadium. Furthermore, the required additional heating for keeping the temperature in the galleries 10°C above outdoors has been determined.

b. Closing the side entrances

From experiences during soccer games in the stadium it had become clear that closing the side entrances (160 m²) has a strong influence on the incoming airflow at field level. Using the AIDA-model, the effect of closing the side entrances has been quantified.

c. The effect of extra clothing insulation

Calculations were made for a clothing ensemble of 1.14 clo (briefs, singlet, shirt with long sleeves, jersey, pants, jacket, socks and shoes) and 1.6 clo (down jacket in stead of normal jacket and an additional fiber-pelt waistcoat). The insulation values are based on the study of McCullough et al. (1985). It should be noticed that the insulation values refer to the total ensemble, including trapped air layer. The insulation values are dependent on air motion.

d. The effect of prohibiting the sales of alcohol and cold fluids

The ingestion of cold fluids decreases core temperature. We calculated the effects of 1–12 glasses of 200 ml drink with a temperature of 6°C (beer temperature) on the mean body temperature (TB) according to formula 1.

\[ T_B' = \frac{(BWt + T_D) + (DWt * T_D)}{(BWt + DWt)} \]  

In which

- \( T_B' \) = Body temperature (0.7*cold temperature + 0.3*mean skin temperature)
- \( T_D \) = Drink temperature
- \( BWt \) = Body weight
- \( DWt \) = Weight of the drink(s)

In case of cold alcoholic drinks (beer) two factors reduce core temperature in the cold. Beer is a cold fluid (6°C) and suppresses the shivering response of the human body that occurs if core temperature decreases (Granberg, 1991). This is probably due to a reduced set point for shivering (Cabanac, 1998). By changing the source code of the Thdyn model (Lotens, 1993), the shivering was decreased by 50% to simulate this effect. This percentage is chosen as the worst case, but is subject to debate since adequate data is lacking on this topic.

e. The effect of mobilizing the audience to increase the metabolism

Heat transfer generally follows an increased metabolism to the environment. In order to achieve an increment in metabolism of the audience, an entertainer was instructed to stimulate the audience to move (dance). The effect of a higher metabolism on the DLE was determined using the IREQ model for the clothing ensemble.

f. The effect of rain protection

The audience had to walk in the open air for about 30 minutes prior to enter the stadium. Taken into account that on the 1st of February 57% of the days over the last 100 years were rainy days in the Netherlands, there was a considerable risk for the audience to get wet. In the worst case the audience would enter the stadium in wet clothing and sit down for the next 5 hours. A simulation of a rain scenario was done using the THDYN model (Lotens, 1993) by omitting the outer clothing layer. It was assumed that the combined effect of evaporative cooling of the wet outer layer and increased heat conduction is similar to zero insulation.

Measurement protocol during the party in the Arena

To evaluate the validity of the model predictions, temperature and relative humidity dataloggers were placed in the stadium at different locations (Fig. 1). The dataloggers were RD-temp (Omega, Stamford, CT, USA) for temperature at the 1st (12 m above the field) and 2nd (32 m above the field) concourse and outside the stadium. A NOMAD temperature-humidity datalogger (Omega, Stamford, CT, USA) was placed at the 1st and 2nd concourse for temperature and humidity determination. The temperature and humidity measurements at the catwalk (35 m above the field) were performed with a Squirrel datalogger (Grant, UK) in combination with a probe HMP45D (Vaisala, SF). At about 17.00 hours the dataloggers were started and the temperature and humidity were recorded every two minutes.

Using a handheld instrument (Testo 491, Finland),
short term measurements (3 minutes averaged values) were made throughout the different zones in the stadium. From these measurements, an evaluation can be made of the differences in temperature between 1st and 2nd concourse.

In order to measure local effects, a heat sensitive camera (ThermoCAM SC2000, Flir Systems AB, Sweden) was directed to a specific part of the stadium. A mean value for the emissivity was set at 0.92 (as a mean value for concrete and human tissue). Both occupied and unoccupied parts of the stadium were analyzed.

**Results**

**Climatic assessment**

The AIDA model (Liddament, 1989) showed that the air change rate is strongly influenced by wind speed and wind direction (Fig. 2). Also, the size of the openings, especially of those at field level, the so-called cheeks, has a big influence. With the ‘cheeks’ opened for 25% ($\pm 40$ m$^2$), the air change rate changes from 0.7 air changes per hour at 2 m/s to 2.1 at 10 m/s. In the latter case, this means that the entire volume of the stadium is replaced in 30 minutes. It is estimated that the audience generates about 4 MW (40,000 * 100 W) of heat. This results in an average temperature increase in the stadium of about 10°C compared to outdoors for an average ventilation rate of 1 air change per hour and about 5°C at a ventilation rate of 2 at a high wind speed (10 m/s). The temperature increase calculated this way refers to the temperature at roof level. Due to the vertical temperature gradient, a lower temperature rise at the 1st and 2nd concourse was assumed. Previously, it was observed that temperatures in a soccer game were about 3°C lower at the 1st concourse as compared to the 2nd concourse. On average, the temperature in the stadium to which the visitors would be exposed was assumed to be about 5°C higher than the ambient temperature. This value of 5°C will be used in the evaluations of different preventive measures (clothing, activity rate, rain protection).

**Assessment of hypothermia risk**

Fig. 3 shows the results of the relation between metabolism (in W/m$^2$) and the duration of limited exposure (in hours) until maximal discomfort is reached, for different ambient temperatures and 1.14 clo insulation.

When the stadium temperature is 10°C (which means an ambient temperature of about 5°C) and people generate 110 W/m$^2$ for 4 hours, the audience would be able to keep themselves warm. If the stadium temperature would be below 0°C (which meant an ambient temperature of $-5°C$), the audience would not have been able to keep themselves warm generating a metabolism of 170 W/m$^2$ for 4 hours. We estimated that the elderly in the audience could not maintain a metabolism of over 170 W/m$^2$. Therefore, we advised the organization to consider canceling the party at ambient temperatures less than $-5°C$.

**Assessment of the effect of preventive measures**

a. Additional heating within the stadium

The results of the use of 2.4 MW of heating in the stadium indicated that for the 1st concourse an average increase of 1 to 3°C above outdoor temperature could be expected, depending on wind speed and wind direction. In view of the costs, it was decided not to use this option.

b. Blocking the side entrances (‘cheeks’)  

The effect of blocking the side entrances is considerable. The average air change rate is reduced from 2.5 air changes per hour to 0.7 with side entrances fully closed. It was decided to block the side entrances as much as possible.
The effect of extra clothing insulation

The effect of extra clothing insulation is shown in Fig. 4. We calculated the effect of having 0.5 to 1.6 clo of clothing. The simulation was done for a metabolism of 110 W/m², stadium temperature of 5°C and relative humidity of 50%. A clothing insulation of 1.6 clo would be sufficient for over 5 hours according to the IREQ-model.

d. The effect of prohibiting the sales of alcohol and cold fluids

Beer intake reduces core temperature due to its temperature of about 6°C and due to the reduction of shivering. The effect of cold drink on the decrease in body temperature, for three different body weights, is shown in Fig. 5. If alcohol consumption reduces the shivering response with 50%, the decrease in body temperature will be 0.8°C (Fig. 6). It was recommended to prohibit the sales of beer during the party.

e. Mobilizing the audience

The entertainer tried to mobilize the audience by inviting them several times to applaud and to perform ‘the wave’ (raising arms while standing). The audience followed the instructions without problems.

f. The effect of rain protection

Rain protection may be important to prevent during the walk to the stadium. The decrease in DLE when the outer clothing is wet, is assessed by a decrease in thermal insulation from 1.14 to 0.69 clo due to removal of the outer clothing layer. To keep themselves warm, people need to generate a large amount of extra heat by increasing metabolism. However, even if they are able to generate 170 W/m², the risk for hypothermia is considerable at ambient temperatures of 0° to 5°C. Therefore, we recommended the organization to supply raincoats.

Temperature and relative humidity during the party in the Arena

It was an exceptionally warm evening during the party (Fig. 7). At the first of February, an afternoon temperature of over 10°C is rare (<6%), and an evening temperature of about 12°C is exceptional. The average wind speed was 11 m/s, direction south-southwest. Using these values, ventilation of 600 m³/s was predicted, corresponding with a ventilation rate of approximately 2. From the temperature model, an increase of the temperature inside the stadium of
5.5°C compared to outdoors was calculated. Fig. 8 shows that the actual ambient temperature rose by about 6°C at the concourses and in the top. Predicted temperatures were thus close to what was measured, except for the vertical temperature differences, which were less than expected. The short-term (handheld) measurements showed temperatures in the different zones of the stadium between 15.8°C and 19.8°C. In contrast with our assumption, temperatures at the 1st concourse were similar to those at the 2nd concourse. This might be explained by the cross ventilation of the stadium, caused by the high wind speed, during the event.

The relative humidity decreased from about 75% at the beginning of the party to 60% at the end. The dew point was constant at about 10.5°C.

Fig. 8 shows three consecutive measurements by the infrared camera of the temperature of an unoccupied part of the stadium. The mean temperature increased from 11.2°C (time 6:32 PM) to 13.3°C (time 7:30 PM) to 15.3°C (time 9:00 PM).

Discussion
Hypothermia risk
Several factors appeared to be present that might have a negative impact on the thermal balance of the visitors during the wedding party: low ambient temperatures could be expected as well as a relatively high wind speed or ventilation rate in the stadium during five hours of inactivity due to sitting. Complicating factors might be underdressing due to misperception of the thermal conditions in the stadium, the potential use of alcohol and the fact that the audience is relatively old and contains several paraplegics.

The IREQ-model (ISO TR 11079, 1993) showed that the metabolism needed to counteract the negative balance was unachievable for ambient temperatures less than −5°C. This would lead to extreme discomfort, which was undesired during a party and might even lead to mild hypothermia. Cooling to mild hypothermia can be very rapid in slim subjects, in particular in wet cold. Thompson and Hayward (1996) observed that one subject cooled with a rate of 2.6°C/hour during walking in the rain. Therefore, the risk for hypothermia was considered as serious.

Preventive measures
Several measures were considered to reduce cold strain. The study with the AIDA model and the ESP-r model showed that the effect of additional heaters was limited, but that reducing the ventilation by blocking the side entrances would be effective.

Model calculations using IREQ showed that clothing insulation was very important and therefore a lot of effort was put into communicating the importance of appropriate clothing. It was decided to send each visitor a letter before the party. The letter recommended bringing insulative clothing and warm shoes. This advice was also printed on each entrance ticket.

Drinking cold beer reduces the heat content of the body and decreases shivering. It is hard to estimate how much shivering is reduced. Graham and Lougheed (1985) observed that body cooling in the cold accelerated through alcohol intake for males, but not for females.

The alcohol intake of the equivalent of four glasses of beer caused an additional drop in core temperature of 0.3°C and skin temperature of about 1°C after two
hours in males. This means an additional cooling due to reduced metabolism of 17 W due to alcohol\textsuperscript{1}. This is about 35\% of the predicted metabolism due to shivering (Lotens, 1993). More information is necessary in order to make good estimates of the effect of alcohol on shivering reduction.

The supply of raincoats was recommended because evaporation of wet clothing during the party inside the Arena would lead to strong additional cooling.

**Evaluation of predictions**

During the event it did not rain and the temperature was exceptionally high. Therefore, it was hard to make a good evaluation of some of the model predictions. However, the increase of the temperature in the stadium, measured by thermistors and infrared camera, corresponded rather well to the predictions.

Most visitors came to the party with raincoats or plastic bags and wore insulative clothing. No hypothermic victims were reported during the evening. Many visitors removed part of the clothing that they wore in order to be in thermal balance. The attempt to mobilize the crowd was successful, the crowd was encouraged to stand up and wave hands in order to increase metabolism. The majority of the crowd participated.

The distance between the visitors in the stadium was large enough to prevent the occurrence of the penguin effect (Blows, 1998), which is the effect that the crowd takes on a ‘corporate body temperature’. In that case heat transfer to the environment is reduced and the temperature rises to very high values.

**Conclusions**

The estimation that the temperature in the stadium would rise by about 6°C on average was confirmed by measurements (5°C rise). Every preventive measure was taken to ensure that the risk for hypothermia would be minimal. The side entrances were blocked to reduce the cold air influx; each visitor received a letter with the recommendation to wear insulative clothing; the sales of beer was prohibited and an entertainer tried to mobilize the audience to generate more heat. The effect of additional heating was estimated to be very small and therefore not implemented.

Calculations of the risk for hypothermia using ISO TR11079 learned that serious problems could be expected at ambient temperatures of less than \(-5^\circ\text{C}\). It was recommended to cancel the party at ambient temperatures less than \(-5^\circ\text{C}\).

Due to the exceptional high temperatures during the party evening, no hypothermia occurred.

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**References**


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\textsuperscript{1} Mean body temperature difference=0.7° Core temperature difference+0.3° Mean skin temperature difference=0.7°0.3+0.3° 1.0=0.5°C. Body heat content change=specific heat*body mass*Mean body temperature=3.4772*0.5=125 kJ. Power=heat content change/time=125 000 J/7200 s=17 W.