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A portable calorimeter for the calibration of thermal manikins

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INTRODUCTION

Human activity has been expanding into the Arctic in recent years through resource development, new polar cruise routes and trans-polar flights [1][2]. These activities are exposing humans to new extremes in a remote, cold environment, where temperatures routinely fall below -20°C and rescue time is measured in days, not hours [3]. Assessment of the system thermal protection offered by garments and shelters for use in the Arctic is critical to ensure the safety of crews and passengers, especially in a survival scenario.

However, these extreme conditions pose real ethical and physiological limits for testing protective gear with human subjects. Exposure to sub-zero conditions has numerous inherent health risks, including hypothermia, cold shock, frostbite and non-freezing cold injury. The necessarily uncomfortable test conditions make recruiting subjects a challenge. Small sample sizes and the variability in subjects' cold responses entail low confidence levels in human testing [4].

Thermal manikins offer an alternative to the challenges of human subject testing. A thermal manikin is a device that mimics heat loss from a human through a control system that maintains an output (e.g., constant surface temperature or power) and measures heat flow. It has a body similar in dimensions to a (standardized) human. Thermal manikins are used in some laboratories and testing facilities to estimate the insulation values for thermal protective clothing and equipment, such as sleeping bags, arctic gear and immersion suits.

Manikins are already accepted in Canada and internationally for approval testing of immersion suits ([5], [6] *et al.*). Yet some manikin results have disagreed with each other in a recent round-robin test [7]. Inconsistent measurements like these results dilute the argument for using manikins in place of human subjects.

The source of inconsistencies between manikins may be methodological or calibration. To systematically understand such inconsistencies, it is necessary to quantify errors due to calibration, experimental methods and calculation. While on an individual basis manufacturers calibrate their manikins and researchers develop and follow good experimental practices, there is neither an industry-wide standard for calibration nor a single methodology for laboratories using thermal manikins. For example, some manikins are calibrated by means of a reference-clothing ensemble. This procedure can demonstrate consistency between tests on a single manikin or among different facilities sharing a common ensemble and procedure, but does not ensure global repeatability or absolute accuracy.

Since manikins are not mass-produced and a variety of designs and procedures are in use, a calibration tool is needed to make manikin data credible and to provide a metric for correlating manikin testing to human subject testing. The IOT has a full-body water calorimeter for calibrating submersible manikins. To facilitate the calibration of manikins, including non-submersible ones in many locations with different environments and procedures, a portable calibration system is proposed.

The objective of this work is to develop a portable calorimeter to test thermal manikins in their native environments (i.e., local environmental chamber, methods and equipment) with a theoretical accuracy in heat transfer measurement from the manikin of about 1%.

DESIGN SPECIFICATION

The portable calorimeter is a heat balance calorimeter that extracts the heat generated by the manikin through water circulating in the walls of the air chamber housing the manikin. The air chamber configuration was chosen to allow testing of thermal manikins, including those that are not designed for immersion. The design specifications are listed in Table 1.

Table 1. Portable calorimeter design specification

Specification	**Test**
maximum dimensions to fit various environmental chambers	min. lab door 1.2 m x 1.8 m, min. ceiling 2.6 m
1% accuracy in net heat flow measurement from manikin	*in situ* calibration
robustness: calorimeter must be shipped to and from other labs multiple times	
minimize conduction between various manikins and calorimeter	no uninsulated contact points min. interior 80 cm x 60 cm x 2 m tall
simple set-up	functional test – lab tech
even cooling: surround manikin with even air temperature, even wall surface temperature	functional test – measure air and wall temperatures
waterproof manikin compartment	functional test – humidity sensor
waterproof exterior	functional test – check for leaks
vertically-hung manikin	
standardized: user-supplied materials must be available at all labs, electrical compatibility	
Lightweight	< 300 kg shipping weight
repairable: use of commercial off-the-shelf components	
Cleanable	

The calorimeter design uses the principle of heat transfer based on the change in temperature of a known mass flow:

$$H_w = c_p * \dot{m} * T_{rel} \tag{1}$$

where the heat removed from the calorimeter through water flowing in the walls is the product of the heat transfer coefficient for water c_p, the mass flow rate $\dot{m}$ and the relative water temperature (change) between inlet and outlet T_{rel}.

UNCERTAINTY ESTIMATE

The significant sources of error in the measured heat transfer from the manikin are assumed to be from the theoretical uncertainty in the calculation (arising from sensor inaccuracy) and from extraneous heat loss through the body of the calorimeter (insulation heat loss).

The theoretical uncertainty of the heat flow measurement can be calculated from the differential form of the heat transfer equation:

$$dH_w = c_p * \left(T_{rel} * d\dot{m} + \dot{m} * dT_{rel}\right) \tag{2}$$

where heat transfer coefficient, c_p is assumed to be constant over the specified small temperature range T_{rel} and the uncertainties $d\dot{m}$ (mass flow rate) and dT_{rel} (inlet and outlet temperature difference) are assumed to be the published specification for commercial off-the-shelf components.

Extraneous heat loss can be predicted by calibrating the calorimeter with a known heat source (such as a hotplate) over the temperature and power ranges of interest.

The presumed accuracy of the system is based on a number of assumptions, listed in Table 2.

Table 2. Design assumptions

calorimeter will be operated in an environmental room capable of control within ±1°C
manikin output at steady state < 300 Watts (estimated manikin output for pump/chiller sizing)
entire system will remain above dewpoint
cooling fluid is supplied by a constant pressure system (open reservoir)
cooling fluid does not become contaminated by system (e.g., corrosion)
ambient environmental room is maintained at the average of inlet & outlet temperatures (heat flow equation remains linear)
all heat loss from manikin due to convection (neglect conduction, radiation is omni-directional)
all heat loss from wall to water and thru the wall is due to conduction (neglect convection cooling within and outside the wall)

PROPOSED DESIGN

In the proposed design, the portable calorimeter is a glass fibre-reinforced polymer (GFRP) box that houses the manikin in a sealed air chamber and removes heat using water flowing through aluminum tubing encased in sheet aluminum walls. The manikin is supported vertically on a gallows with minimal contact (nylon straps and hook or bolts). The inside surface of the aluminium walls are painted black to facilitate heat absorption. This configuration is shown in the figures below.

Figure 1 & 2. Proposed portable air calorimeter (front and top views) [8]

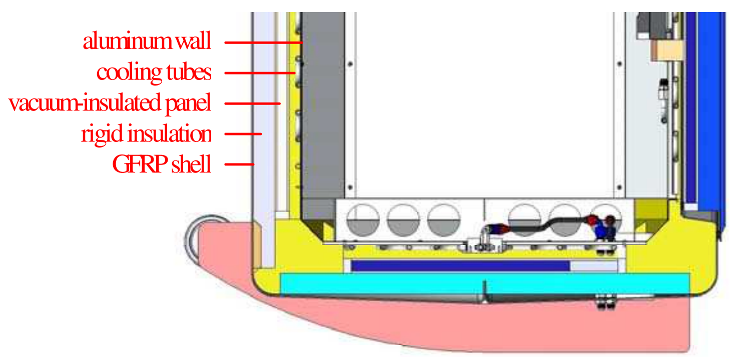

Figure 3. Calorimeter wall cross-section [8]

The cooling fluid is pumped through manifolds to all sides of the chamber; its temperature is controlled with a peltier (thermo-electric) chiller. To prevent stagnation from creating any significant temperature profile across the walls, the air inside the chamber is stirred with a small, low energy fan of known heat loss.

The heat transfer from the manikin is calculated from the temperature rise and the mass flow rate of the cooling fluid (distilled water). A theoretical accuracy of 1.27% in manikin heat transfer can be achieved with a calibrated coriolis-effect mass flowmeter (±0.2 g/s) and paired thermistors (± 0.01°C).

To minimize extraneous heat loss through the walls, the calorimeter is insulated with vacuum-insulated panels filled with aerogel, an extremely low-density porous solid. Based on the insulation values for vacuum-insulated panels, aluminum and GFRP, these losses are estimated to be less than 1% of the manikin power output. During test conditions, it is expected that the calorimeter would be calibrated with a controlled heat source before each use to determine the total extraneous heat loss as an offset in the heat transfer calculation. The integrity of the vacuum insulation is confirmed using interior surface heat flow sensors on each chamber wall.

The chamber is sealed with an airtight door. The humidity in the chamber is measured with a humidity sensor to ensure that the system operates above the dewpoint and that the manikin is not exposed to excessive moisture.

The proposed calorimeter is designed for shipping complete with the accessories (pump, chiller, reservoir and data acquisition system) and to operate inside a variety of facilities around the world, relying on universal power supplies, minimal set-up and only distilled water added by the user. It is sized to fit a wide profile of the manikins currently in use in their particular environmental facility.

RECOMMENDATIONS FOR FUTURE WORK

A portable calibration tool for thermal manikins could help to eliminate calibration as a possible source of error and facilitate cross comparison of manikin results. If the industry collaborates to set a standard calibration procedure and users periodically re-calibrate their thermal manikins, thermal manikins will gain credibility and wider acceptance for testing in lieu of human subjects.

Although funding to manufacture the portable calorimeter has not been secured, it is hoped that this work could entice interest from manufacturers and test laboratories in a joint project to establish a well recognized manikin calibration procedure and calibration tool.

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