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Budget-limited thermal biology: Design, construction and performance of a large, walk-in style temperature-controlled chamber

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ABSTRACT

We describe a partial redesign of the conventional air-conditioning system and apply it to the construction of a relatively large (1.87 m^3 air mass), walk-in style temperature-controlled chamber (TCC) using parts easily obtained in most countries. We conducted several tests to demonstrate the performance of the TCC. Across the physiologically relevant range of 5–37 °C, the TCC took 26.5–50.0 min to reach the desired set point temperature. Once at set point, temperature inside the chamber was controlled with an accuracy of ± 1.0 °C. User-entry effects on deviations from and return times to set point temperature were minimal. Overall, performance of the TCC was sufficient to make precise physiological measurements of insect metabolic rate while controlling assay temperature. Major advantages of the TCC include its simplicity, flexibility, and low cost.

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1. Introduction

Temperature is a fundamental determinant of biology (Gates, 1980; Cossins and Bowler, 1987; Johnston and Bennett, 1996; Angilletta, 2009). Therefore, the ability to control temperature experimentally is fundamental to many lines of biological inquiry, which has motivated the development of a wide variety of custom-made enclosures (e.g., Moos et al., 1965; Schoen, 1972; Grace and Shipp, 1988). Commercially available temperature-controlled enclosures range in size and complexity from bench top incubators to room-sized, walk-in climate-controlled chambers. Increasingly, these units have high-level programmability to simulate variable thermal regimes, including simulation of real-time, site-specific climates. The functionality, precision and accuracy of these instruments make them a solid long-term investment for any well-funded laboratory with routine needs to control temperature. However, commercially available units can be cost-prohibitive and outside the budgetary scope of small-scale research endeavors, especially those requiring large, walk-in chambers.

Here, we demonstrate and test a flexible means by which temperature can be controlled efficiently, accurately, and precisely using relatively inexpensive materials that are easily procured in most countries. Our approach involves a partial redesign of the conventional air-conditioning system and is applicable to assay temperatures above 0 °C. After first describing the technology, design and specifications of our custom-made temperature-controlled chamber (TCC), we present a quantitative analysis of its performance and demonstrate its application as a walk-in incubator to study insect metabolism. This specific application reflects our own interests, but there are undoubtedly many other potential applications within biology and other disciplines.

2. Materials and methods

2.1. Design and construction

A common design of commercially available temperature-controlled units and many inventions (Albert and Leo, 1930; Wendschlag, 1983; Linhardt and Rosener Jr, 1999) employs direct heat exchange between a refrigerant and conditioned air. These designs are highly space-efficient, with the conditioning units fully embedded within the enclosure structure. This unified design between the air conditioning system and the enclosure unit reduces clutter and maximizes laboratory space, but greatly reduces the potential for user modifications and repairs. In terms of air conditioning technology, various designs utilize water as a heat

Abbreviations: TCC, Temperature-controlled chamber; HMHE, Hydro-mediated heat exchange

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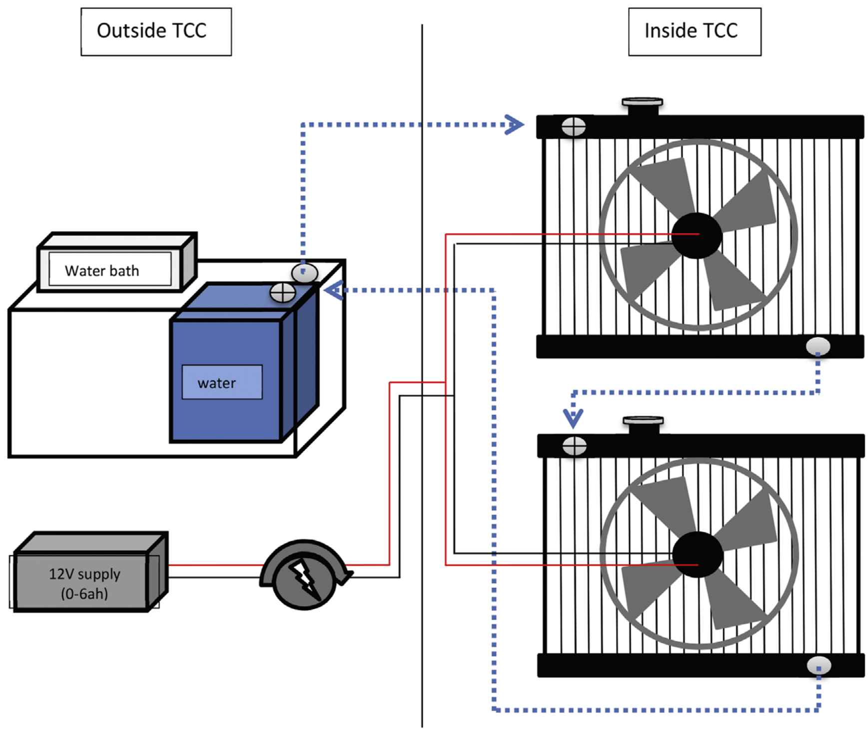

Fig. 1. Conceptual diagram of hydro-mediated heat exchange (HMHE) in a temperature controlled chamber (TCC). Conditioned water in a recirculating water bath passes through a series of heat exchangers. Most of the current technologies utilize water as a refrigerant heat sink during the condensation phase. Here, water is utilized as an intermediary between the refrigerant and the air.

sink during the refrigerant condensation phase, based on a previous invention (Latimer, 1987). However, to our knowledge, a design that uses water *in lieu* of the refrigerant in an air-water heat exchanger apparatus to control air temperature has yet to be described. Due to its heat capacity, water is a suitable fluid to condition an air mass (Green, 2008), particularly when set point temperatures are within normal physiological range. Although the exchange of heat between water and air is slow compared to the exchange between refrigerants and air, using water as a heat exchanger allows users to easily modify the heat exchanging apparatus to fit their application. Since to our knowledge this technology has not been previously described, we will refer to it as *hydro-mediated heat exchange* (HMHE), which is employed in the TCC described in this study.

The basic components needed to implement the HMHE technology described above are listed in Table A1. They include a water conditioning system (i.e. water bath) capable of circulating conditioned water (plus 10% isopropanol to minimize fouling) through one or more radiator cores (Fig. 1). We used automobile-type, 2-row radiator cores connected in series to the water conditioning system (Table A1, Figs. 1 and 2). Each radiator core is connected to an automobile-type radiator cooling fan, which condition the air by drawing it perpendicularly through the radiator cores (i.e., single phase, cross-flow radiative heat exchange). If desirable, an optional current regulator can be connected to the fans to control air flow and direction (Fig. 1). To create a TCC, the HMHE system is integrated with a well-insulated enclosure as seen in Fig. 2. We used a relatively inexpensive commercially available steel enclosure, insulated with a combination of 2.54 cm and 5.08 cm polystyrene sheeting cut to fit the enclosure from the interior (Fig. 2, Table A1). Alternatively, polyisocyanurate is a more effective insulator than polystyrene and could be used at increased cost.

2.2. Performance: conditioning of a 1.87 m^3 air mass

To test the performance of the TCC in approaching and remaining at a temperature set point, eight temperature sensors (U23-004; Onset Computer Co., Bourne, MA, USA) and one temperature/relative humidity sensor (U23-001; Onset Computer Co., Bourne, MA, USA) were spaced strategically (8 corners and floor center) throughout the chamber. At each assay temperature (5, 10, 20, 30 and 37 °C), intermediate fluid (i.e. water plus 10% isopropanol) was brought to the set point temperature in a water bath prior to circulation through the radiators. To account for differences in temperature between incoming and outgoing water, we determined the offset between the set point temperature of the water bath and the chamber at each assay temperature (Table A2). Once the water bath reached the set point temperature (with offset), the radiator cooling fans were supplied with approximately 12 W (12 V, 1.0 Ah) through a current regulator. The chamber door was closed, and the water bath's circulating valve was opened to allow conditioned water to pass through the radiators at a rate of approximately 4.0 L min^{-1}. Internal chamber temperature was monitored from outside with a 450 AKT thermocouple (OMEGA, Stamford, CT, USA). Once the chamber reached set point temperature, it was allowed to equilibrate for 30 min prior to user entry trials.

Short-term user entry and exit effects on chamber temperature were determined at each assay temperature by a user entering (door opened and closed immediately) and remaining in the chamber for 30 s. Long-term user entry and exit effects were

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