Designing a Better Baby Warmer for Energy-Insecure Geographic Regions

Kyle Combes Onur Talu

October 1, 2017



Figure 1: Our experimental setup, which is a scaled-down version of our life-sized model.

Contents

1	Executive Summary	3
2	Design Considerations	3
3	System Definition and Analysis	4
	3.1 Model	4
	3.2 Thermal Model	4
	3.3 Governing Thermodynamic Equations	5
	3.4 System Control	6
	3.5 Governing Systemic Equations	7
4	Performance of the Model	8
	4.1 Simulation	8
	4.2 Experimentation	9
	4.3 Determining K_p and K_I	9
	4.4 Expected Behavior	10
	4.5 Actual Behavior	11
5	Design Recommendations	12
R	eferences	13

1 Executive Summary

In developing countries, one of the leading causes of newborn fatalities is hypothermia. While health facilities in developed countries can afford sophisticated incubation equipment along with the necessary training, facilities in developing countries do not have the resources to follow suit. This leaves countless newborns, especially those born prematurely, at serious risk for hypothermia. For our work, we decided to take a closer look at the baby heating device developed by one of the Olin College Affordable Design and Entrepreneurship (ADE) teams.

During this project, our goal was to glean insight into how they might develop a better device for these underserved regions. Doing so would require satisfying multiple constraints, namely cost, energy consumption, performance, and ease of use. We decided to focus primarily on minimizing energy consumption while still attaining satisfactory performance, as a large percentage of the developing world is limited by inadequate power supply[1]. This required conducting a systemic analysis of the thermodynamic model and control system, both on paper and through experimentation at scale. In the end, we were able to formulate a set of design recommendations for those looking to construct such a device.

2 Design Considerations

When designing our system, we decided to focus on three goals: minimizing cost, minimizing power consumption, and maximizing performance, which we defined as the time until the target temperature was reached. The rationale and specifics for each design goal (summarized in Table 1) were derived from several important factors affecting baby warming devices and the facilities in which they are used.

First, one of the prevailing problems in hospitals of the developing world is the difficulty in meeting the demand for health services. It is not uncommon to arrive at a hospital only to spend hours in the waiting room, stalled by insufficient resources. Since it is crucial to provide the baby warming service to those who need it quickly, a primary design goal was to reach the desired body temperature quickly. We (somewhat arbitrarily) defined the upper bound on our acceptable heating time to be 45 minutes. Furthermore, according to [2], the body temperature of a healthy baby should only fluctuate by 0.5°C. More severe fluctuations can prove hazardous to the health of the baby. Therefore, our warming device needed to keep the baby within this temperature window once the target temperature was reached.

An additional significant limiting factor is whether or not reliable electricity is available[1]. Oftentimes, health facilities rely on diesel generators with maximum output constraints, or on electric grids that cannot support severely fluctuating demand. Thus, we decided our device needed to be able to operate under these restrictive conditions. According to [3] and [4], the average power consumption for person in US hospitals is about 200 watts. Using this number as a sort of best-case scenario for continuous operation, we decided our system should be easily configurable to draw no more than the US average for use in severely constrained environments.

Finally, since this baby warmer is intended to be used for both healthy and hypothermic babies, the system would need to perform well for a range of starting temperatures. We decided a comprehensive range was from 30° C to 35° C.

Table 1:	Design	Goals	and	Metrics
----------	--------	-------	-----	---------

Goals	Metrics
Fast Climb to Desired Temperature	$\leq 45 \min$
Low Power Consumption	$\leq 200W$
Desired Temperature with Room for Error	$37.5 \pm 0.5^{\circ}C$
Different Starting Baby Temperature	30 to 35 $^{\circ}C$

3 System Definition and Analysis

3.1 Model

The initial prototype developed by the ADE team utilized polycarbonate for the bassinet and with a flat heating element attached to its bottom. We decided to continue using this approach, as polycarbonate is cheap, sturdy and thermally conductive and the design overall proved highly portable and rugged. A visual representation of the system can be seen in Figure 2.

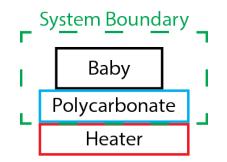


Figure 2: The system diagram of the baby warmer.

3.2 Thermal Model

The system was modeled with two-stock, four-flow thermal diagram, as seen in Figure 3. Several assumptions were made in order to simplify this system to such a degree:

- There was thermal inflow to the polycarbonate through the heater. All the thermal output of the heater was transferred to the bassinet, without losing any of its power to the surroundings.
- The polycarbonate bassinet lost this energy to the baby through conduction and to the surroundings through convection.
- As seen in Figure 2 above, the polycarbonate bassinet was assumed to be a single planar pad with heat lost only through the top surface.
- A baby was placed in the heating pads without any additional insulating material, or the insulating properties of these materials were neglected.
- The baby's only source of heat loss was convection to surroundings, and there were no physical disturbances to the system that would result in some other form of heat outflow.
- Heat generated by the baby (due to its metabolic processes) was ignored.

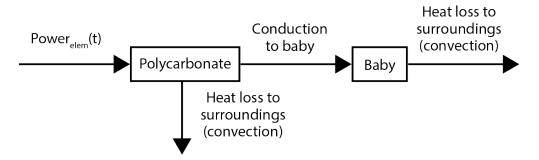


Figure 3: The thermal stock and flow model of the system.

As seen in Figure 3 above, there were two stocks to keep track of: the internal energy of the polycarbonate bassinet and of the baby. Since body temperature was a measure that aligned with this system's goals better, the temperatures of these two bodies were used in modeling equations, rather than internal energies. This was achieved by dividing the internal energy by the corresponding body's mass and specific heat.

3.3**Governing Thermodynamic Equations**

The thermal system depicted in Figure 3 was modeled using the system of ordinary differential equations comprised of Equations 1 and 2, where P(t) was the power output by the heating element at time t and T_{bass} and T_{baby} were the temperatures of the bassinet and baby, respectively, with respect to room temperature.

$$\frac{T_{bass}}{dt} = \frac{P(t)}{m_{bass}c_{bass}} + \frac{k_b A_{contact}(T_{baby} - T_{bass})}{m_{bass}c_{bass}d_{bass}} - \frac{h_{air}A_{bass}(T_{bass})}{m_{bass}c_{bass}} \tag{1}$$

$$\frac{T_{baby}}{dt} = \frac{k_b A_{contact}(T_{bass} - T_{baby})}{m_{baby}c_{baby}d_{bass}} - \frac{h_{air}A_{baby}(T_{baby})}{m_{baby}c_{baby}} \tag{2}$$

(2)

Table 2: ODE Variables

Variable	Meaning	Value
T_{bass}	Temperature of the bassinet, with respect to the room temperature	Dependent
T_{baby}	Temperature of the baby, with respect to the room temperature	Dependent
P(t)	Power output of the heating element	Dependent
m_{bass}	Mass of the bassinet	0.25kg
m_{baby}	Mass of the baby	3kg
c_{bass}	Specific heat capacity of the bassinet	$1200\frac{K}{Jkg}$
c_{baby}	Specific heat capacity of the baby	$4000\frac{K}{Jkg}$
k_b	Thermal conductivity of the bassinet	$0.2 \frac{W}{mK}$
hair	Heat transfer coefficient of air at $25^{\circ}C$	$10\frac{W}{m^{2K}}$
d_{bass}	Thickness of the walls of the bassinet	0.005m
$A_{contact}$	Area of contact between the baby and the bassinet	$0.05 \ {\rm m}^2$
A_{bass}	Surface area of the bassinet that does not touch the baby	$0.075m^2$
A_{baby}	Surface area of the baby that does not touch the bassinet	$0.25m^{2}$

Due to the overabundance of	variables, the	e equations	were simplified	via the gro	uping of
variables, as laid out in Table 3.3.					

Constant	Grouped Variables
α_1	$m_{bass}c_{bass}$
α_2	$\frac{k_b A_{contact}}{m_{bass} c_{bass} d_{bass}}$
α_3	$h_{air}A_{bass}$
α_4	$\frac{m_{bass}c_{bass}}{\frac{k_bA_{contact}}{m_{baby}c_{baby}d_{bass}}}$
$lpha_5$	$\frac{h_{air}A_{baby}}{m_{baby}c_{baby}}$

Table 3: Grouping the constants in our ODEs greatly simplified the equations.

Thus, the thermodynamic equations became

$$\frac{T_{bass}}{dt} = \frac{P(t)}{\alpha_3} + \alpha_1 (T_{baby} - T_{bass}) - \alpha_2 (T_{bass})$$
(3)

$$\frac{T_{baby}}{dt} = \alpha_4 (T_{bass} - T_{baby}) - \alpha_5 (T_{baby}) \tag{4}$$

3.4 System Control

Since a design goal was to reach the desired temperature as quickly as possible, choosing an appropriate control system was of paramount importance. Proportional (P) control is the simplest and most common, but a downside is a significant steady-state error (between the desired and actual temperatures). Proportional-integral (PI) control builds on proportional control by adding an integral component, and is thus slightly more complex. Fortunately, the integral component serves to ameliorate essentially all steady-state error. Lastly, proportional-integral-derivative (PID) control further extends PI control, with the added derivative component allowing control over the system temperature overshoot.

Intent on using the simplest effective approach possible to minimize error, we started with proportional-integral control. Fortunately, we found this performed satisfactorily for our conditions and no overshoot was apparent. With PI as our chosen control, our system could be sketched as shown in Figure 4, with difference of the desired temperature (D) and the current baby temperature (Y) being the input into the control block in the center.

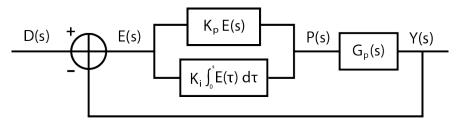


Figure 4: We designed our system to use a proportional-integral (PI) controller, which is represented by the two stacked blocks in the center. As input, it receives the difference between the desired temperature (D) and the current baby temperature (Y).

3.5 Governing Systemic Equations

In our particular model, the system output that we were monitoring was the baby's temperature. Thus, for any time t

$$y(t) = T_{baby}(t) \tag{5}$$

Taking the Laplace transformation of both sides, to move to the s-domain, gave us

$$Y(s) = T_{baby}(s) \tag{6}$$

Using this fact, we combined the thermodynamic equations from Section 3.3 to find the plant function, G_p , for our system.

$$G_P = \frac{Y(s)}{P(s)} = \frac{T_{baby}(s)}{P(s)} = \frac{\alpha_4}{\alpha_3(s^2 + \alpha_1 s + \alpha_2 s + \alpha_4 s + \alpha_5 s + \alpha_2 \alpha_4 + \alpha_1 \alpha_5 + \alpha_2 \alpha_5)}$$
(7)

The same logic was applied to the find the controller function, G_c .

$$G_c = K_P + \frac{K_I}{s} \tag{8}$$

In a closed-loop system, the overall transfer function is $H(s) = \frac{G_c}{\frac{1}{G_P} + G_c}$. Therefore, the transfer function for our system was as follows.

$$H(s) = \frac{G_c}{\frac{1}{G_P} + G_c} H(s) = \frac{K_P + \frac{K_I}{s}}{K_P + \frac{K_I}{s} + \frac{\alpha_3(s^2 + \alpha_1 s + \alpha_2 s + \alpha_4 s + \alpha_5 s + \alpha_2 \alpha_4 + \alpha_1 \alpha_5 + \alpha_2 \alpha_5)}{\alpha_4}$$
(9)

Then, in order to find the values of K_P and K_I that would lead to critical damping (or the fastest convergence to the target temperature), we solved for the roots of the denominator of the transfer function. For a 3kg baby, the values turned out to be those shown in Table 3.5.

Constant	Values
K_P	39.9917
K _I	0.0150

Table 4: The critical damping values for a 3kg baby, which lead to the fastest convergence to the desired steady-state temperature.

Plugging these values for K_P and K_I into the equation for the baby's temperature resulted in the following equation:

$$Y(s) = 2.5 \times 10^{-6} + 0.0073632s + 2.8625s^2 + 300s^3 \tag{10}$$

With the baby's temperature in the s-domain determined, all that was required to get the temperature in the time domain was to take the inverse Laplace transform of the function. This resulted in Equation 11, which we would later use to find the temperature of a baby placed in our system with an initial temperature of 35° C at any time t.

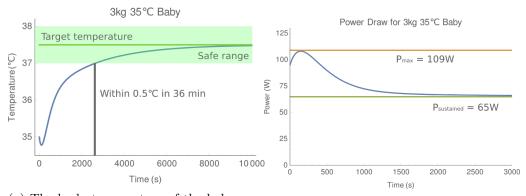
$$T_{baby}(t) = 15.5 + 4.01574e^{-0.00566248} - 4.98451e^{-0.00345299t} - 1.53124^{-0.000426204t}$$
(11)

4 Performance of the Model

Once we had our model and system defined, we ran various simulations and one physical experiment to test the validity of our model.

4.1 Simulation

Using the values for K_I and K_p derived in Section 3.5, we simulated two 3kg babies with starting temperatures of 35°C and 30°C. We then plotted the babies' temperatures and the heating units' power draw against time, as can be seen in Figures 5 and 6.

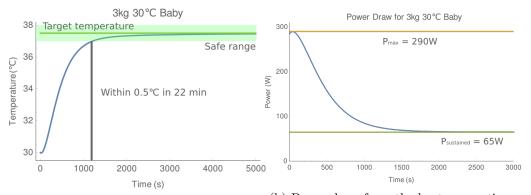


(a) The body temperature of the baby over(b) The power draw of the heater over time.

Figure 5: 3kg baby with 35°C initial temperature

As is particularly apparent in Figure 5a, when the baby's starting temperature is considerably above the room-temperature bassinet, the baby's thermal energy initially flows into the bassinet, heating it up. When the bassinet has reached the baby's temperature, there is no longer any net heat flow between the baby and the bassinet, and the derivative of the temperature curve is zero. As the bassinet continues to be heated by the heating element, it begins to heat the baby.

When the baby begins at a temperature of 35°C, the power draw of the unit stays well within our established 200W maximum (Figure 5b). However, if one were to place a severely hypothermic, 30°C baby in the bassinet, the power draw would spike to nearly 300W (Figure 6b). Thus, we realized we would need to implement a control mechanism to prevent this from happening.



(a) Body temperature of the baby over time (b) Power draw from the heater over time.

Figure 6: 3kg baby with 30°C initial temperature

4.2 Experimentation

To test our model, we conducted a scaled-down experiment. A Ziploc bag of water served as our baby (since babies are roughly 80 percent water[5]), and we used a small piece of Lexan and some wire mesh heating elements to act as our bassinet. The heating elements rested on an insulating folded cloth to minimize heat loss out the bottom. An image of the setup can be seen in Figure 9.

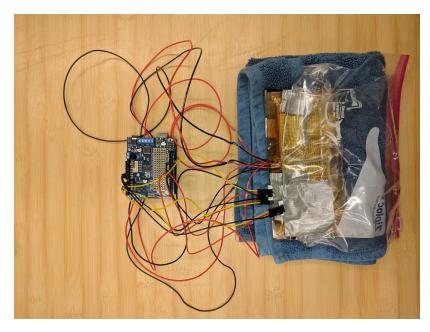


Figure 7: Our experimental setup, with a bag of water acting as our baby and a piece of Lexan acting as our bassinet.

The heating elements were driven by an Arduino and Adafruit Motor Shield, and the temperature was monitored at various points in the system using several thermistors (though only the water temperature influenced the control behavior). A complete list of our experimental materials can be found below.

- 1x Arduino Uno R3
- 1x Adafruit Motor Shield v2.3
- 1x USB type A male to USB type B male cable
- 1x 12V AC power adapter

- 3x Temperature probes
- 1x 4x12x0.5cm polycarbonate (Lexan) slab
- 1x Ziploc Slider bag
- 100g Water
- 4x 5V 5x15cm heating elements
- Duct tape

When conducting our experiment, we began with 28°C water. While this didn't directly reflect any of our anticipated real-world conditions, it was still valid for testing the behavior of our model.

4.3 Determining K_p and K_I

Before running our experiment, we needed to determine appropriate values for K_I and K_p in our scaled system. Using the procedure outlined in Section 3.5, we settled on a value of 1.145×10^{-3} for K_I and a value of 1.153 for K_p .

4.4 Expected Behavior

With our K_I and K_p calculated, we then adjusted the system parameters in our model and ran a simulation. We found that our setup should reach within have a degree of our target temperature in about 1.3 hours, as can be seen in Figure 8. (In actuality, we didn't run this simulation until after we ran the experiment and, in the experiment, we accidentally set the desired temperature to 37°C instead of 37.5°C. By the time of writing this, it was too late to go back and rerun the experiment, so there is simply a minor discontinuity in the desired temperature throughout this report.)

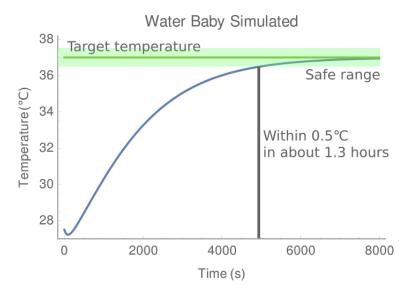


Figure 8: Our experimental results concur with our model. Though the numeric values are off, due to this being a scaled version, the overall shape is correct.

4.5 Actual Behavior

By and large, we found our experimental behavior reflected that of our simulation. The exact rate of temperature increase was a little off, and thus so was the time to reach our desired temperature range. This was probably mainly due to the rough calculations and assumptions we made when modeling the system initially. However, the general shape of the curve and overall system behavior is consistent between the simulation and reality (Figure 9).

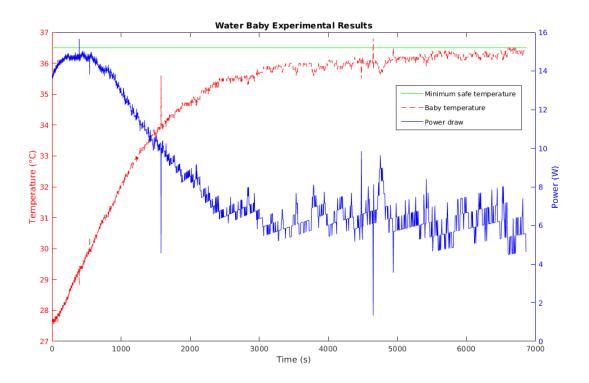


Figure 9: Our experimental results concur with our model for the most. Though the time to reach our safe temperature range is a little off (about 2 hours vs about 1.3), this is likely due primarily to the assumptions and simplifications we made when initially constructing our model.

5 Design Recommendations

Using our model, we were able to determine how long it would take to reach steady state vs the maximum power draw of the system. We simulated this for a severely hypothermic 3kg baby with an initial temperature of 30° C and plotted the behavior, which can be seen in Figure 10.

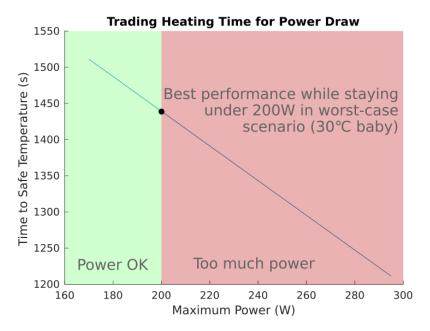


Figure 10: Simulating a worst-case scenario of a severely hypothermic baby ($T_0 = 30^{\circ}$ C), we determined that it would take about 1440 seconds to reach the lower bound of our safe operating temperature (37°C) while restricting the power consumption to 200W. Choosing a different maximum power threshold would result in different warming times, as illustrated.

Given our insights, we would recommend future design work include incorporating some sort of P_{max} control, whereby the operator could limit the maximum power draw of the system. This could be something as switch toggling between "Performance" and "Limited," or it could be a multi-setting dial for more granular control.

We can also confidently say that a proportional-integral control system is suitable for this application. Heating time was satisfactory and steady-state error was practically nonexistent.

However, more work should be done toward minimizing the heating time. Babies of different masses should also be simulated, and the phenomenon whereby a baby with a higher initial starting temperature takes longer to reach the desired temperature should be investigated as well. Futhermore, the maximum power draw threshold of 200W was somewhat arbitrarily chosen, so more research should be done to determine whether this value is realistic or not.

Moreover, our findings are simply a first pass at understanding the relationship between baby warmer performance and power consumption. Each one should be taken with a grain of salt.

References

- H. Adair-Rohani, K. Zukor, S. Bonjour, S. Wilburn, A. C. Kuesel, R. Hebert, and E. R. Fletcher. Limited electricity access in health facilities of sub-saharan africa: a systematic review of data on electricity access, sources, and reliability. *Global Health: Science and Practice*, 1(2):249–261, Jan 2013.
- [2] Disabled World. Human body temperature: Fever normal low readings.
- [3] U.s. energy information administration eia independent statistics and analysis.
- [4] AHA Hospitals. Fast facts on us hospitals, Dec 2016.
- [5] USGS Howard Perlman. The water in you.