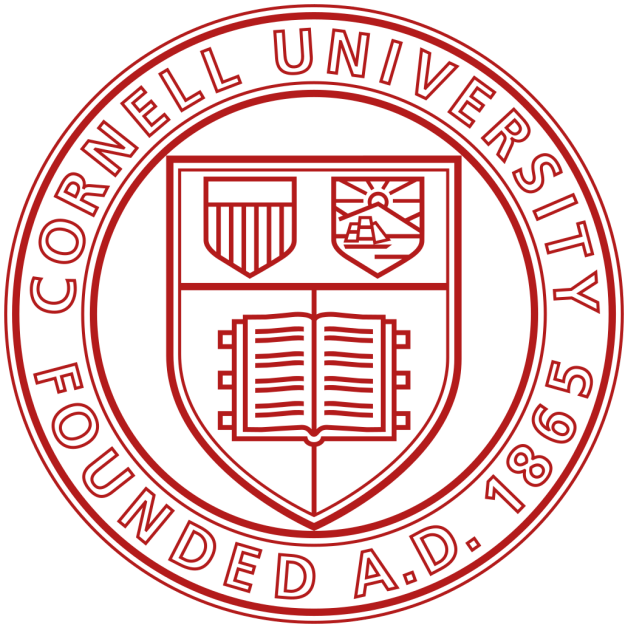
Heat Transfer in Penguin Huddles

Samson Karben, Glenn Kim, Ivanakbar Purwamaska, Caitlin Tormey



Keywords: Penguin, Huddling, Numerical Model, COMSOL, Heat Transfer, Fluid Flow

BEE 4530: Computer-Aided Engineering | Applications to Biological Processes

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1.0 Executive Summary

Emperor penguins have several adaptations that allow them to survive the extreme Antarctic winter. Some of these adaptations are behavioral, such as huddling to reduce exposure and preserve body heat. While previous research has been done to estimate the metabolism of individual emperor penguins, these birds often group together, and thus less heat is lost than the equation suggests. The paper will focus on modeling a full penguin huddle where the penguins are exposed to ambient temperature and wind typical of Antarctica to see what spacing is necessary to maintain a typical body temperature and where the best place to stand in the huddle is. The numerical solver used in this report is COMSOL, a multiphysics modeling software that allows for a high degree of flexibility and accuracy. Each penguin is modeled as a 2-D circle with heat generation and insulation parameters determined by previous research. The penguin was copied 6,000 times to form a hexagonal huddle. The physics modeled are fluid flow and heat transfer in fluids and solids. We found that a spacing of between 0.8cm and 0.951cm allows the penguins in the penguin huddle to maintain the average body temperature of 38.2°C, the typical penguin body temperature (Le Maho, 1976). In addition, the optimal location of minimal heat loss was determined to be the middle towards the back. This simulation could allow for new insights and methods into research of how the huddling of the penguins preserves body heat and how changing conditions, due to climate change, could affect penguin behavior and survival in such a hostile environment.

2.0 Introduction

2.1 Background

Emperor penguins live in Antarctica, the coldest continent on earth. During the Antarctic winter, ambient temperatures can drop as low as -40°C and wind speeds can reach 140 km/h (McCafferty, 2013). Staying warm is key to both survival and reproduction, especially since emperor penguins are the only penguins with a breeding cycle during the Antarctic winter (McCafferty, 2013). In order to stay warm, emperor penguins form huddles to minimize their overall heat loss during periods of extreme cold and wind. The paper will analyze the relationship between individual penguin heat loss, individual penguin location in a penguin huddle, and ambient Antarctic air flow through the use of a numerical model. The numerical model will fully-couple heat transfer and fluid flow.

Heat Generation, Insulation, and Huddle Formation

Heat loss in emperor penguins is a function of the gradient between body and ambient temperature, which is dependent on heat generation, insulation, and surface area exposed to the ambient conditions. Emperor penguins generate heat to stay warm with a carefully regulated

metabolism, which is dependent on weight and ambient condition exposure (Gilbert, 2008). Breeding emperor male penguins weigh on average 30 kg and are 1.2 m tall (Gilbert, 2008). In order to fuel this metabolism, penguins have to burn their body fat that they have been accumulating all summer. On average, grouped birds in free-ranging formation and loosely spaced formation are found to lose between 132 and 178 g/day (Gilbert, 2008). As a comparison, isolated birds on average lose 299 g/day, around double the value (Gilbert, 2008). Although this weight loss is insignificant in our simulation, it does show the immediate benefit of huddling to reduce the rate of heat generation in each penguin. The same review paper also compiled detailed equations on field metabolic rate, specific to different ambient condition exposure that will be used in this paper.

Heat generation is important to staying warm, but it is also important that the heat generated does not immediately transfer to the surroundings. To combat the rapid heat transfer, emperor penguins have excellent insulation from their skin, feathers, trapped-air, and down. Several studies have been done to model heat transfer through the insulating layers. A model based on physical scans of penguin skin and feathers was done to model thermal conductivity, the degree to which a material is able to conduct heat (Dawton, 1999). The model assumed evenly distributed feathers and found thermal conductivity to be 2.38 W/(m^2*K), comparable to the measured experimental value of 1.93 W/(m^2*K) (Dawton, 1999). To build on the previous model, a numerical model of penguin feathers and down was done (Du, 2007). The numerical model used a finite volume model and found thermal conductivity to be 1.73 W/(m^2*K) (Du, 2007). Both studies argue that the thermal conductivity of feathers is accurate to represent the penguin's insulation system as a whole. The argument is well-supported because empirically measured values are done on one layer of skin attached to the feather. However, a more recent study has found that actual penguin feather distribution is more complicated than a single, evenly distributed layer. Analysis of emperor penguin carcasses lead to the discovery of more complex feather structures and greater contribution of down as insulation (Williams, 2015). Although true thermal conductivity of emperor penguin's insulation system may be slightly different, we plan to use the empirically measured value of 1.93 W/(m^2*K) as it has been measured and is referenced in most papers on the subject.

Amid drastic temperature drops and strong winds, heat generation, and insulation alone are insufficient to maintain the optimal temperature and huddling is needed to minimize heat loss. Smaller animals like emperor penguins benefit from huddles due to large combined surface area to combined volume ratio. Huddles last for minutes to hours, depending on ambient conditions (Waters, 2012). Depending on the ambient temperature, huddle density may be as high as 10 penguins/m^2 and appear semi-static (Gu, 2018). In a penguin huddle, individual penguins approximately obtain equal access to the warmth of the huddle through complex reorganization movements. Penguin huddles have been observed to have extremely slow motion (Le Maho,

1977). A study by Le Maho concluded that the penguins with the most surface exposed windward slowly moved leeward (Le Maho, 1977). The windward-leeward movement is repeated and produces a slow, peeling movement in the penguin huddle as a whole (Le Maho, 1977). However, Gilbert's (2007) study shows that cold induced huddling episodes lasted longer than wind induced huddling, which appear to continually break and reform (Gilbert, 2007). Therefore, huddling dynamics induced by ambient conditions appear to be more complex than previously thought.

Previous Research

Due to harsh conditions in the Antarctic, observational and experimental studies of emperor penguin huddles are complex and costly. The use of numerical models provides a viable alternative to investigate heat loss and movement in a penguin huddle. A numerical model approach is not common in penguin studies, but would be helpful in understanding the physics of heat transfer that drive the penguin huddle behavior. One previous study developed a numerical model of a shifting solid against fluid flow to model the movement of a penguin huddle in Antarctic conditions (Gu, 2018). The Navier-Stokes equation for fluid flow was approximated using finite difference and smoothed particle hydrodynamics. The study accurately predicted how penguin huddles shift but does not take into account individual penguin nor penguin huddle heat loss. Another previous study developed a numerical model to model a penguin huddle and investigated heat loss and movement of the penguins as a group, see Figure 1 (Waters, 2012). The polygon was randomly generated but individual penguin's movement was driven by the intent to minimize surface exposure, the penguin huddle does achieve an even distribution and a nearly uniform heat loss distribution. However, the model does not capture quantitative values of individual penguin heat loss and the effect of insulation.

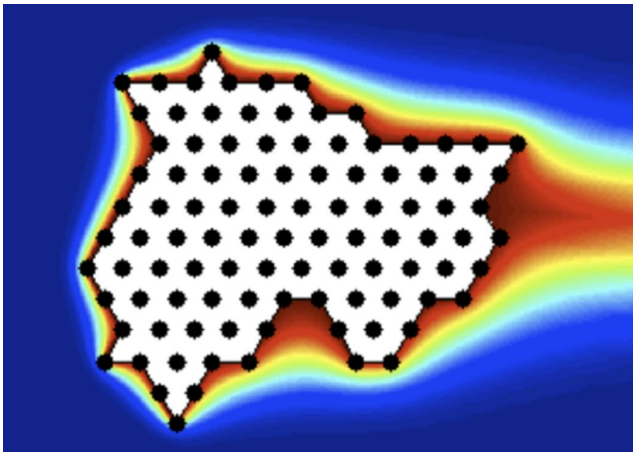

Figure (1). The temperature distribution around a polygon huddle of 100 penguins (Waters, 2012). Red represents warmer temperatures, while blue corresponds to cooler temperatures. The

black circles represent penguins, white areas represent the polygonal interior of the huddle. The figure demonstrates an initial configuration pre-relocation.

2.2 Problem Statement and Design Objectives

We aim to build a numerical model of a penguin huddle to better understand these research questions:

1. The effect of spacing between individual penguins on the temperature of the huddle.
2. The optimal location within the temperature to balance heat loss with overheating from being too close to other penguins.

Spacing between individual penguins will be varied to determine the ideal amount of spacing without the average huddle temperature overheating. To evaluate the average huddle temperature, this paper provides quantitative measures of body temperature and heat loss of individual penguins that depend on the gradient between penguin and ambient air temperature, ambient air speed, and penguin position within the penguin huddle. Each penguin is modeled as a 2-D concentric circle with heat generation in the middle and thermal insulation in the exterior. The numerical model of the penguin huddle will be able to quantitatively estimate heat transfer of individual penguins within a penguin huddle.

3.0 Methods

To investigate these research questions, a model was created to capture all the relevant and necessary physics as well as geometry. The section will outline the problem formulation and how the model will be implemented.

3.1 Geometry

Penguins form in large masses as shown in Figure 2 below.

Figure (2): Typical formation of an emperor penguin huddle. The general shape is polygonal and there are several thousand penguins in the photograph. *Emperor penguin colony*, 2006, https://en.wikipedia.org/wiki/Emperor_penguin#/media/File:EmperorPenguinColonyClose.jpg.

To model this large mass of penguins, some assumptions and simplifications had to be made about the geometry. Penguins were assumed to be cylindrical, following the model assumptions done by Ning Du's paper "An improved model of heat transfer through penguin feathers and down" (Du, 2007). In addition, the huddle can be modeled in a hexagonal shape as seen in Gilbert et. al. 2008. Huddles contain thousands of penguins, usually 5,000 - 6,000 individuals (Le Mao, 1977, p. 681). The model here will contain 6000 penguins, arranged as seen in Figure 3.

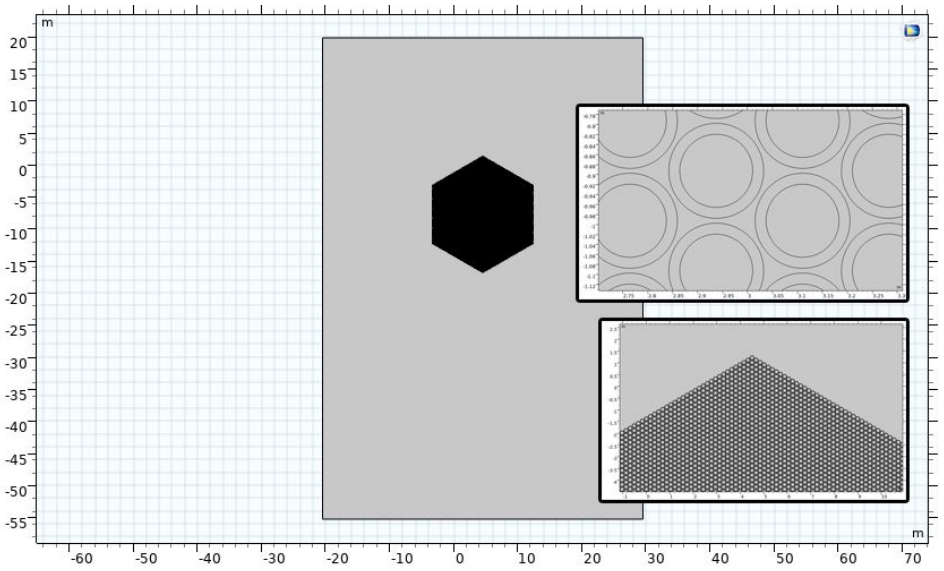

Figure (3): The geometry as seen in COMSOL. The bottom right close-up represents the topmost portion of the hexagonal formation, and the upper close-up represents a closer look at individual cylinders. The penguin, represented by each cylinder, has a radius of 0.0951m (Du, 2007) with the spacing between each penguin extending 0.008m. The outer circle of each penguin represents a feather layer of thickness 0.22mm (Du, 2007). The inflow boundary is the top of the rectangle and the outflow is the bottom and sides of the rectangle.

3.2 Mesh

For the computational model of the 6000 penguins in a huddle, the COMSOL preset "Normal" was chosen for the model, constructed using free triangular elements as seen in Figure 4. However, the number of edge elements per penguin was raised to 6 edge elements per quarter circle, or 24 total per penguin boundary shown in Figure 5. As a result of the geometry, the mesh in the region around the penguins was much more dense than the region outside the huddle which is seen in Figure 6. This denser region was needed to handle the faster change in temperature in the region immediately around the penguins.

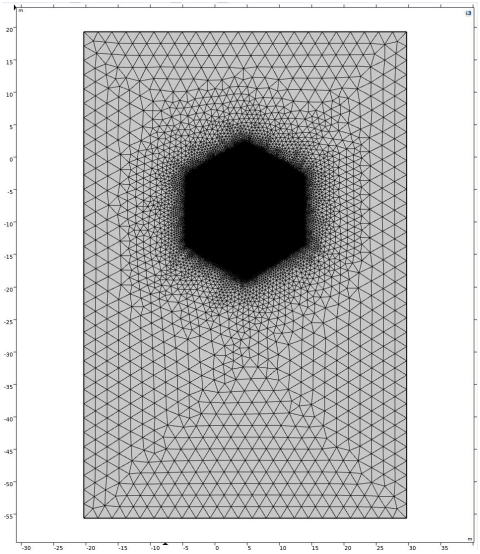

Figure (4): Full free triangular mesh for the penguin huddling model. We see that the mesh is coarse on the edges and gets increasingly finer closer to and within the huddle. The element size is calibrated for fluid dynamics. The maximum element size is 2.25 m and the minimum element size is 0.1 with a maximum element growth rate of 1.15. The number of elements is six edges, which was chosen as a result of the results of mesh convergence.

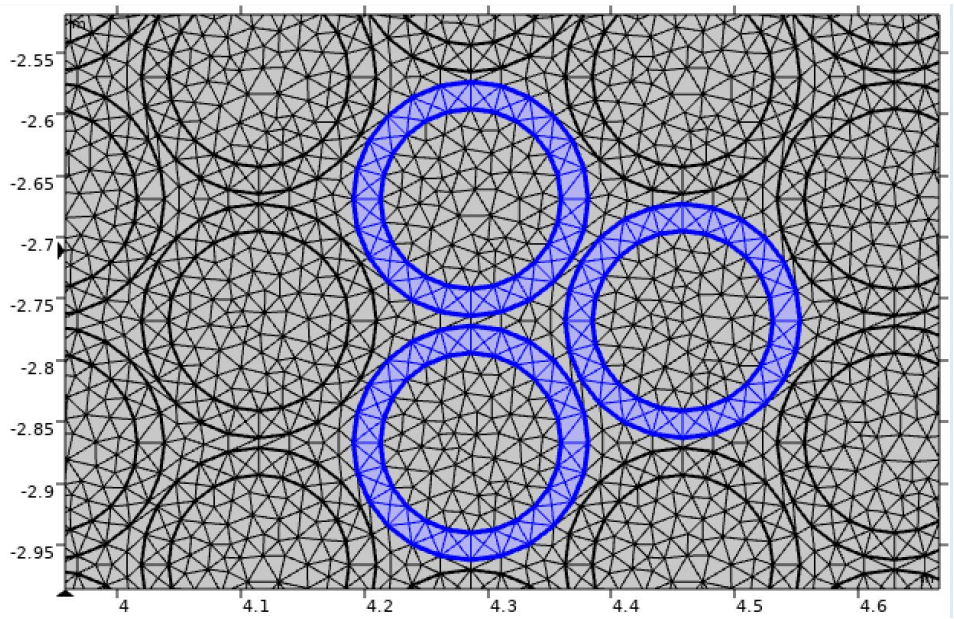

Figure (5): Mesh around the edges of the modeled penguins (the feather region). Note the six edges and seven nodes per quarter circle (24 elements per circle). The number of edge elements directly correlates to total elements in the mesh. We changed the edge elements because of the interest in heat flux on the boundary; we are able to obtain a finer mesh on the surface.

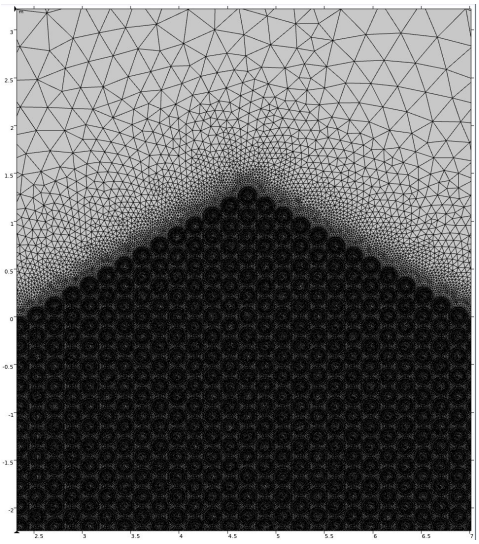

Figure (6): A zoomed in image of the change in mesh density. This comes from the region around the penguins and the region in the bulk air outside the huddle. The figure shows that the mesh is very dense around the penguins where the temperature and velocity will be changing the most.

3.3 Governing Equations

The physics of this model can be described using two governing equations in three different domains. The domains are the penguin core, the feathers, and the ambient air. Heat transfer occurs in all three domains, and thus, the heat transfer governing equation must be solved in all three areas through the use of Heat Transfer in Solids and Fluids COMSOL Physics. Fluid flow from wind occurs only in the air domain, and thus the fluid flow governing equation is solved only in this domain through the use of Turbulent Flow COMSOL Physics

Domain of Penguin Core for Heat Transfer in Solids and Fluids

The objective of the model is to find the average body temperature and the heat flux of the boundary of each penguin. The function describing temperature is $T_{core}(r, \theta)$ where r and θ are spatial variables in cylindrical coordinates and T_{core} describes the temperature of the penguin core. Equation 1 gives the governing equation to be solved for the heat transfer in the penguin core domain.

$$k_{core}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T_{core}}{\partial r}) + \frac{1}{r^2}(\frac{\partial^2 T_{core}}{\partial \theta^2})\right) + Q = 0 \quad (1)$$

Here, it is assumed that the penguins are at steady state (temperature is not changing over time) and that the only relevant types of heat transfer are conduction and generation. The heat generation term, Q, is the metabolic heat generation for each penguin. From Gilbert et. al. 2008, this generation is a function of ambient temperature, T_{air}, and the wind speed, v_{air}

$$Q = [1.08 - 0.08T_{air}] + [\frac{(bv_{air}{}^{0.5})}{M}] \quad (2)$$

where M is the body mass in kg and b is given by

$$b = 0.0092\, m^{0.66}(T_{air} + 10)^{0.32} \quad (3)$$

where m is the body mass in g. Combining Equations 1, 2, and 3 gives the full heat transfer equation in the penguin domain.

Domain of Penguin Insulation for Heat Transfer in Solids and Fluids

Similarly, the function describing the temperature of the feathers is $T_f(r, \theta)$ where r and θ are also spatial variables in cylindrical coordinates. The temperature term is related to thermal

conductivity k_f, specific heat c_f, and the density ρ_f of the feathers. Equation 4 gives the governing equation to be solved for the heat transfer in the penguin core domain.

$$\frac{k_f}{\rho_f c_f}\left(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T_f}{\partial r})+\frac{1}{r^2}(\frac{\partial^2 T_f}{\partial \theta^2})\right)=u_r\frac{\partial T_{air}}{\partial r}+\frac{u_\theta}{r}\frac{\partial T_{air}}{\partial \theta} \quad (4)$$

Here, it is assumed that the temperature of the penguins is at steady state and that the only relevant types of heat transfer are conduction and convection.

Domain of Ambient Air for Heat Transfer in Solids and Fluids

The surrounding air is also described by the temperature function $T_{air}(r,\theta)$ where r and θ are spatial variables in cylindrical coordinates. Equation 5, the heat transfer equation for air, contains a convection term described by the velocity of the fluid air u_r and u_θ. The temperature is related to thermal conductivity k_{air}, specific heat c_a, and the density, ρ_a, of air.

$$\frac{k_{air}}{\rho_a c_a}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_{air}}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T_{air}}{\partial \theta^2}\right)=u_r\frac{\partial T_{air}}{\partial r}+\frac{u_\theta}{r}\frac{\partial T_{air}}{\partial \theta} \quad (5)$$

Here, it is assumed that the heat transfer between the penguins and the air is at steady state and that both conduction and convection are occuring.

Domain of Ambient Air for Turbulent Flow

The cold air flowing across the penguins is considered to be turbulent fluid flow modeled and the velocity, u_r and u_θ, are found using Equation 6 and Equation 7. The air enters the domain flowing from top to bottom. μ describes the viscosity of the air itself.

$$\rho_{air}\left(u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{{u_\theta}^2}{r}\right)=\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru_r)\right)+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2}-\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}\right] \quad (6)$$

$$\rho_{air}\left(u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}-\frac{u_r u_\theta}{r}\right)=\mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru_\theta)\right)+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}\right] \quad (7)$$

Here, we assume that the fluid flow is at steady state and that there is constant pressure and altitude. Thus we only need the inertia and viscosity terms in each direction.

3.4 Boundary Conditions and Initial Conditions

In order to solve the governing equations outlined above, conditions for temperature and velocity at the boundaries of the model must be used in order to find the numerical solution for the fluid flow and heat transfer in and around the huddle. The four relevant boundaries are the inlet, the outlet, and the sides of the huddle, all sufficiently far away from the huddle shown in Figure 7.

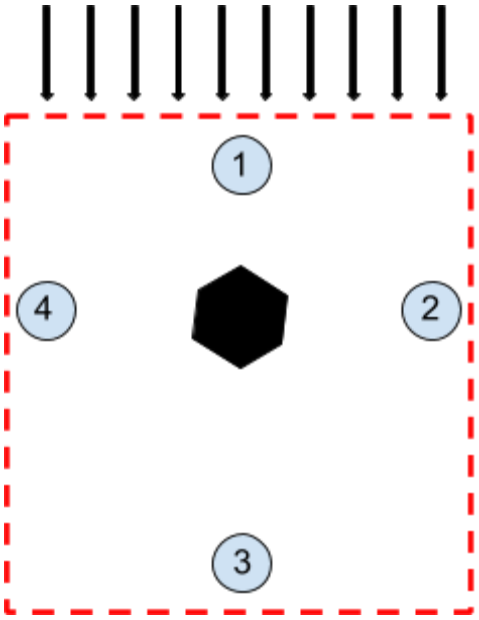

Figure (7): Schematic of the boundaries of the model geometry. Boundary 1 is the inlet where the wind flows into the domain. Boundaries 2, 3 and 4, act at outlets where wind and heat can leave the system. The black hexagon shows the location of the huddle relative to these boundaries.

At boundary 1, the temperature boundary condition is given by Equation 8, where T_{fL} is the average ambient temperature in Antarctica (Gilbert, 2008). The velocity equation at boundary 1 is given by Equation 9, where v_{wind} is the average velocity of the Antarctic wind (Gilbert, 2008).

$$T|_{y=L} = T_{fL} \tag{8}$$

$$v|_{y=L} = v_{wind} \tag{9}$$

At boundaries 2, 3, and 4, both the velocity and heat flux boundary conditions will be set as outflow conditions. This tells COMSOL that there is continuity at the boundary and that the inflow must be equal to the outflow. However, since details are not known about how much heat or air is leaving from each boundary, the general outflow condition must be used.

Although initial conditions are not as important when running a steady state model, the initial conditions used in this model are given by Equations 10, 11, and 12.

$$T_{penguin,\,i} = 40°C \tag{10}$$

$$T_{air,\,i} = T_{fL} \tag{11}$$

$$v_{air,\,i} = v_{wind} \tag{12}$$

The rest of the material properties used in the model can be found in section 10.1 of the appendix.

3.5 Turbulence Modeling

The turbulence model that was used is a RANS type model that uses the Reynolds-averaged Navier–Stokes equations to solve the equations of motion for fluid flow. Specifically, the k-ε model was used as it is best for external flow around bluff bodies (Frei, 2017). The model solves for the turbulence kinetic energy (k) and the rate of dissipation (ε) using several constants. We used the preset constants (given below) that are standard for this model.

$C_{\varepsilon 1} = 1.44$	$\sigma_k = 1$
$C_{\varepsilon 2} = 1.92$	$\sigma_\varepsilon = 1.3$
$C_\mu = 0.09$	$\kappa_v = 0.41$
	$B = 5.2$

4.0 Results and Discussion

Each penguin generates heat through metabolism but this alone is not enough to face ambient air temperature and velocity of the Antarctic. A penguin huddle of 6,000 is formed to maintain a critical penguin temperature of 38.2°C (Le Maho, 1976). The penguin huddle reduces the surface area of the penguins as a whole that directly interacts with the ambient air temperature and velocity. The results below reflect that this reduced exposure to cold and wind allows the penguins to stay warmer than if they were alone.

4.1 Velocity Profiles

The air flows downward towards the penguin huddle at 5 m/s. The overall air velocity profile is displayed in Figure 8 and highlights a stagnation point, a turbulent wake area, and two locations where the flow speeds up around a curved edge. The penguin huddle acts as a bluff body due to the tight packing of individual penguins, which slows down the air velocity to zero to produce a stagnation point in front of the penguin huddle. The air slows at the back of the penguin huddle due to the blockage effect of the huddle.

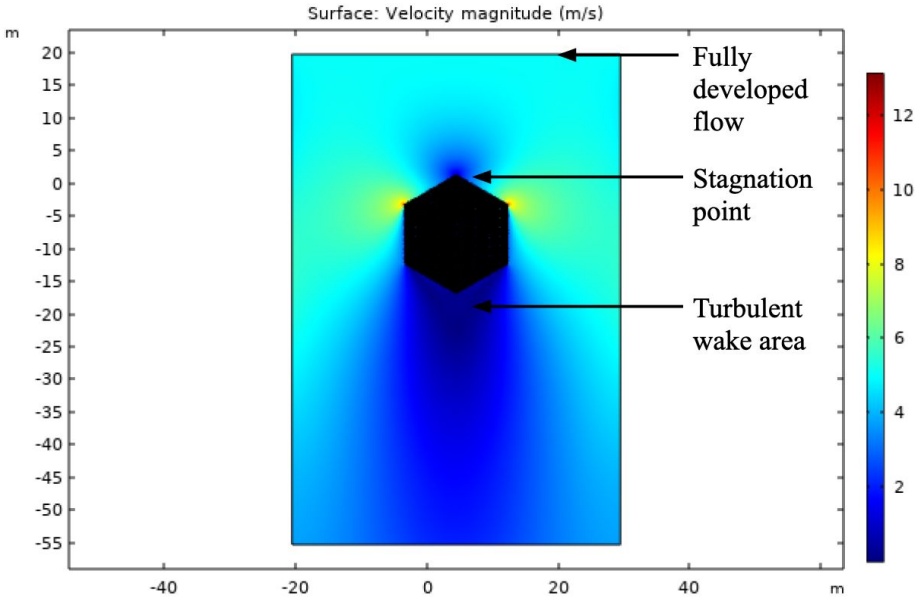

Figure (8): The air velocity profile around the penguin huddle. The color scale gives the velocity in units of meters per second. The top boundary of the region shows the expected velocity of 5 m/s that was set as the boundary condition. The flow slows (blue) in two locations. One is at the stagnation point at the top of the huddle (where the flow is completely blocked by the point of the huddle). The other is in the wake of the huddle where flow is slow because the huddle blocks air flow. The flow speeds up (red) around the top two corners of the huddle.

After being in contact with the penguin huddle, the air increases turbulence and speeds up around the corners. This effect is seen most at the top two curved edges of the hexagon, which produce two areas of increased velocity as shown in Figure 9. The air velocity does speed up between the narrow spacing of penguins at the edge of the penguin huddle. In the middle of the penguin huddle, however, the air velocity becomes zero due to the complete sheltering of air flow by the surrounding penguins which is also seen in Figure 9 and Figure 10.

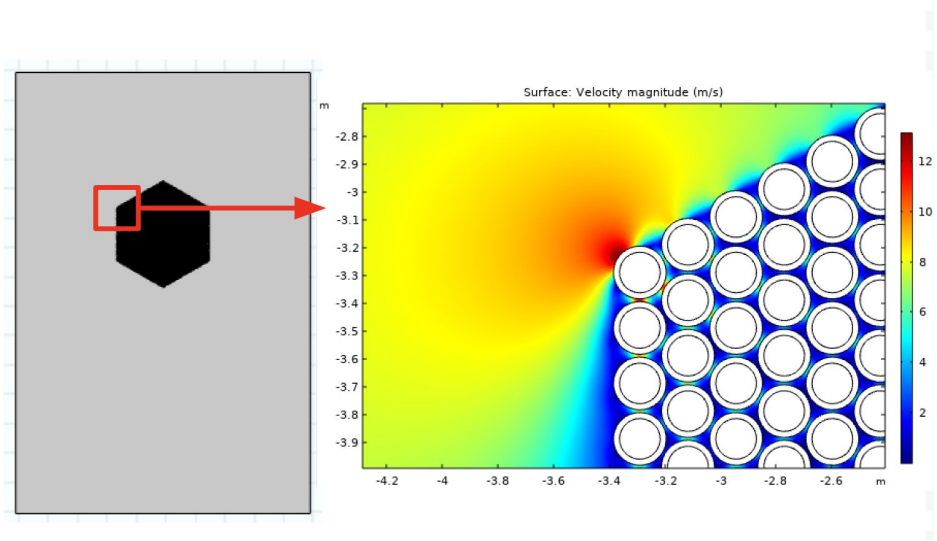

Figure (9): One of two areas of increased air velocity. The velocity is maximum as it passes over the curved section of the corner because it has to speed up around the edge. There are areas of increased velocity between individual penguins near the outer section of the penguin huddle. However, the effect is not apparent in the middle section of the penguin huddle.

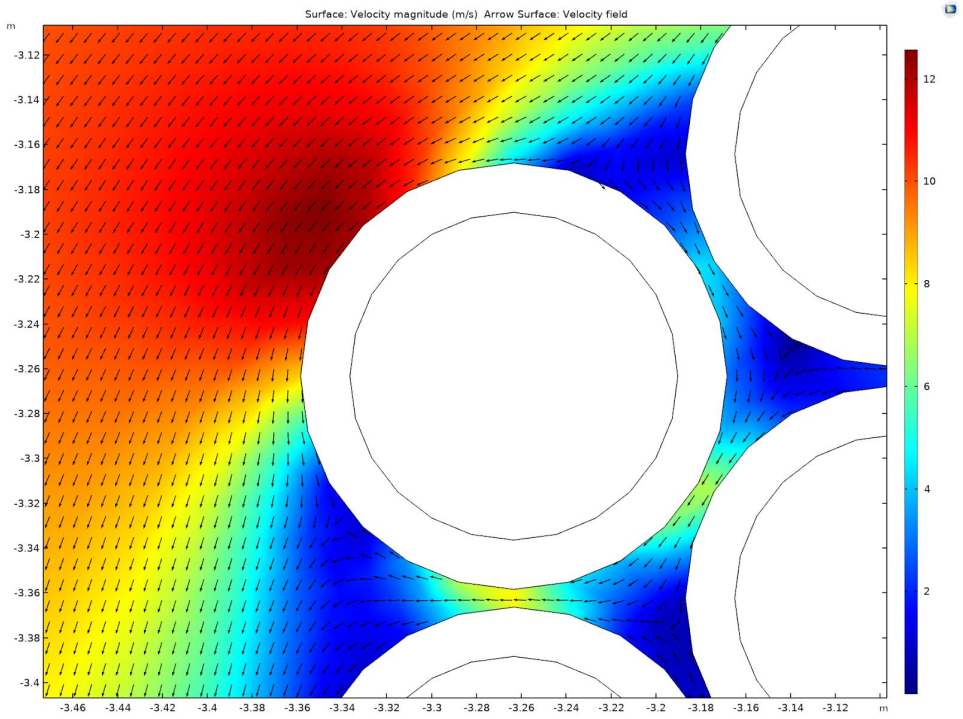

Figure (10): Closer look at one of two areas of increased velocity with the vector field. Each vector is magnitude proportional. Velocity is maximum when air passes around the corner penguin. Additionally, velocity speeds up at the closest area between individual penguins.

4.2 Temperature Profiles

The air flow enters the domain at -16.6 ℃. The overall air temperature profile is displayed in Figure 11 and highlights that the aforementioned turbulent wake area (seen in Figure 9) heats up the most. As the air flow slows down at the back of the penguin huddle, heat convection from the penguins to the air is also slowed down to produce a turbulent wake area where air and individual temperature is high.

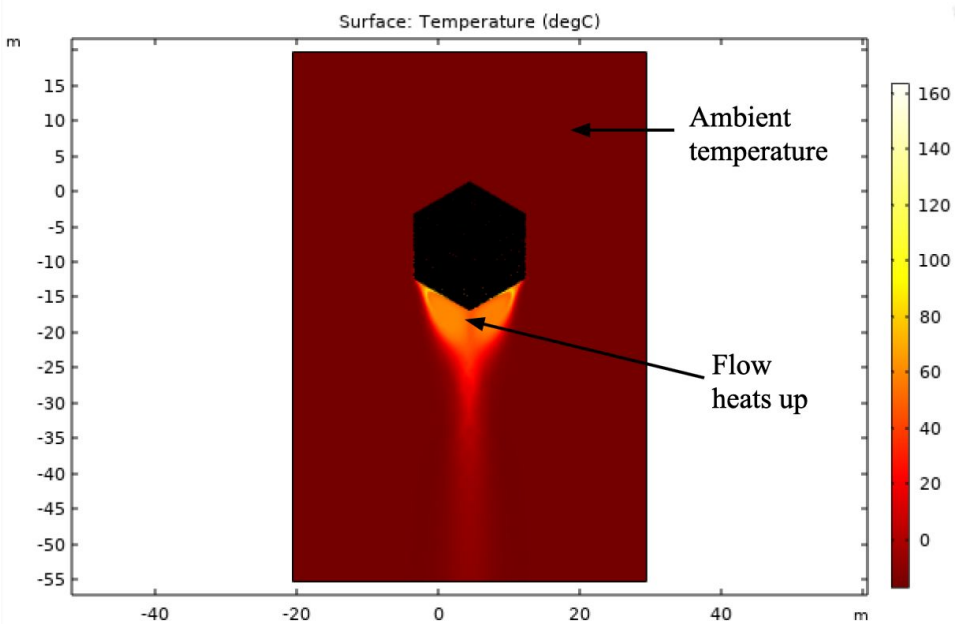

Figure (11): The air temperature profile around the penguin huddle. The temperature around the huddle is the same as the initial and boundary temperatures of -16.6 ℃. The air then heats up at the turbulent wake as the air passes around the penguins and gains heat through slow convection.

The temperature profiles of penguins in several locations within the huddle is shown in Figure 12 to highlight the warmest and the coldest locations. We see that the penguins are warmest at the back end of the penguin huddle due to maximum shelter and maximum effect of turbulent wake area. The coldest penguins in the huddle are those at the top of the huddle that are exposed to the most extreme cold and wind.

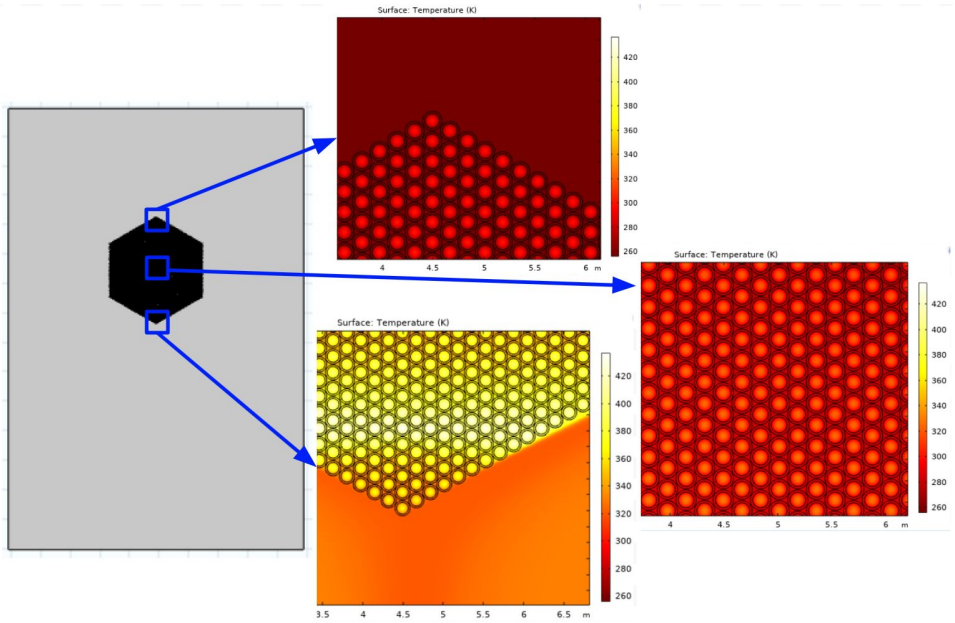

Figure (12): Temperature profiles of penguins for several locations in the huddle. The penguins at the front of the huddle have a red color and are thus the coldest while the penguins at the bottom of the huddle are yellow and white so therefore are the warmest. This is consistent with what is expected as penguins tend to shift towards the back of the huddle when they get too cold (Gilbert, 2008).

4.3 Temperature and Heat Flux with Different Penguin Huddle Spacing

In order to see how the distribution of penguin body temperature within the huddle changes depending on spacing, the same model was run but the spacing was changed as a function of the penguin radius. The original model had the penguins separated by the radius of the penguin divided by twelve; the closest COMSOL could mesh without having them touching. Figures 13 and 14 show a representative sample of measured body temperatures and outer boundary heat flux of the penguins at different huddle locations for a penguin huddle with spacing between penguins of r.penguin/12 = 0.80[cm], r.penguin/10 = 0.951[cm], r.penguin/5 =1.902[cm], r.penguin/2=4.755[cm]. The magnitude of spacing was selected in relation to the penguin's radius because there were limited references to penguin huddle spacing in literature.

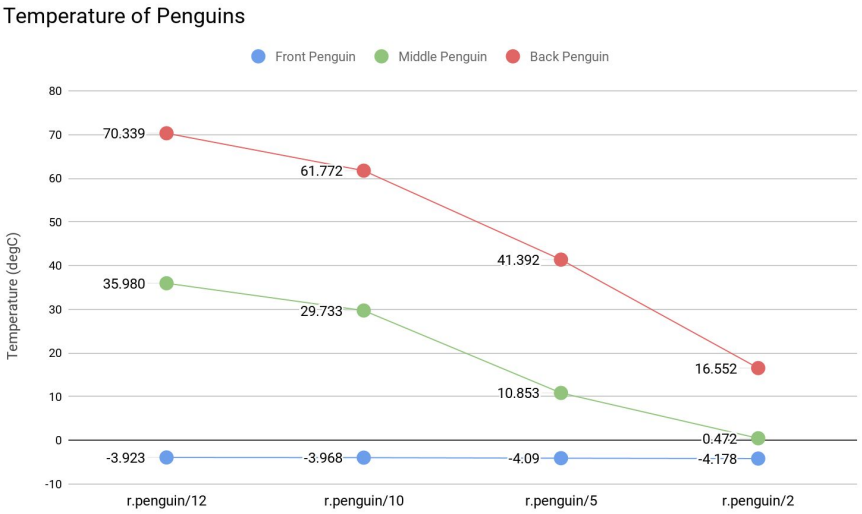

Figure (13): Body temperature of penguins at various locations in the huddle. In each case, the temperature decreases as the spacing increases (except in the front where it stays relatively constant). The penguins in the front are always the coldest and the penguins sheltered in the back are always the warmest. Tables of this data can be found in section 10.2 of the appendix.

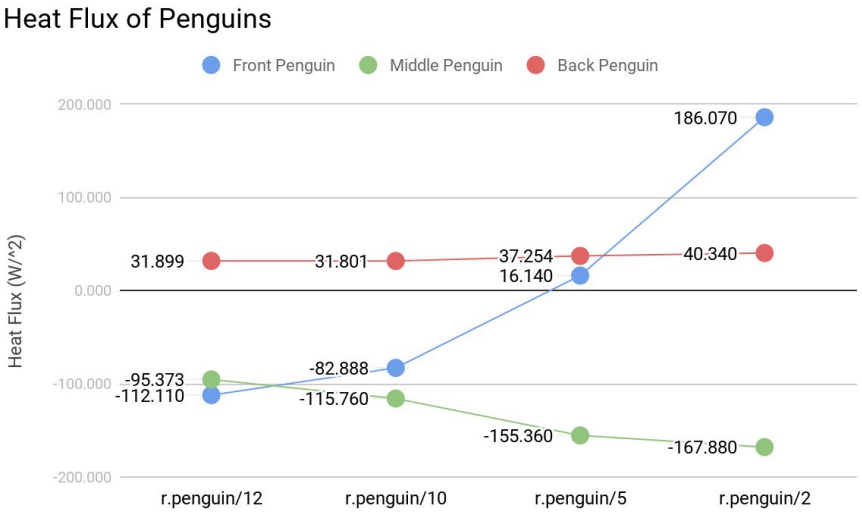

Figure (14): Heat flux of penguins at various locations in the huddle. The back penguins have a relatively constant heat flux and seem unaffected by the change in spacing. The middle penguins are constantly gaining heat. The front penguin gains heat when the spacing is small because the velocity in the front is so low. However, when the spacing is larger, it loses heat because the air is able to flow around and thus it loses heat by convection. Tables of this data can be found in section 10.2 of the appendix.

We see that in each case, temperature increases as penguins move away from the front of the huddle. In addition, the temperature of each penguin increases when the spacing is closer together due to increased conduction between the small amount of air between the penguins and the reduced air flow between them. The heat flux for each case is very similar for the penguins in the back suggesting that their heat flux is not affected by the spacing. However, the penguins in the front seem to benefit more when the spacing is reduced because they lose significantly less heat than penguins in the front of the huddles with wider spacing because the airflow is so slow at the front. In addition, the penguins in the middle of the pack gain heat from the penguins around them because there is no air flow to cool them.

4.4 Optimal Spacing

To determine the ideal spacing in a penguin huddle, we look to Table 1 for the average huddle temperature. Ideally, penguins would like to maintain an ideal body temperature of about 38.2°C (Le Maho, 1976). The best spacing would be one where the average individual penguin body temperature is at or close to this value. We assume penguins are constantly moving around within the huddle (Gilbert, 2008), thus the average individual penguin body temperature, represented by the average huddle temperature, is close to the ideal body temperature.

Table (1): Average temperature of all penguins in penguin huddles with different spacing.

Penguin Huddle Spacing (m)	**Average Huddle Temperature (°C)**
r.penguin/12 = 0.80[cm]	42.919
r.penguin/10 = 0.951[cm]	35.738
r.penguin/5 = 1.902[cm]	13.641
r.penguin/2 = 4.755[cm]	1.432

The spacing of 0.80 cm has the highest average huddle temperature of 42.919°C. However, this is higher than the optimal penguin body temperature of 38.2°C. This body temperature would be achieved by a penguin huddle with a spacing between individual penguins of between 0.951 cm and 0.800 cm.

4.5 Optimal Location Within the Huddle

While it is hard to define an “optimal location” since environmental conditions can drastically change the temperature of the huddle, there is a most and least sheltered location, with a gradient of shelter between them. This simulation shows the least sheltered location to be at the very front of the huddle, and the most at a band towards the back of the huddle.

We can also find the penguins in the model that have an ideal body temperature (38.2°C). This would most likely be the ideal location within the huddle because the penguin is able to maintain the perfect body temperature at this location at steady state and would not need to move around to warm up or cool down over time. Figure 15 below shows one location where the penguins measured a body temperature of 38.2°C ± 0.2.

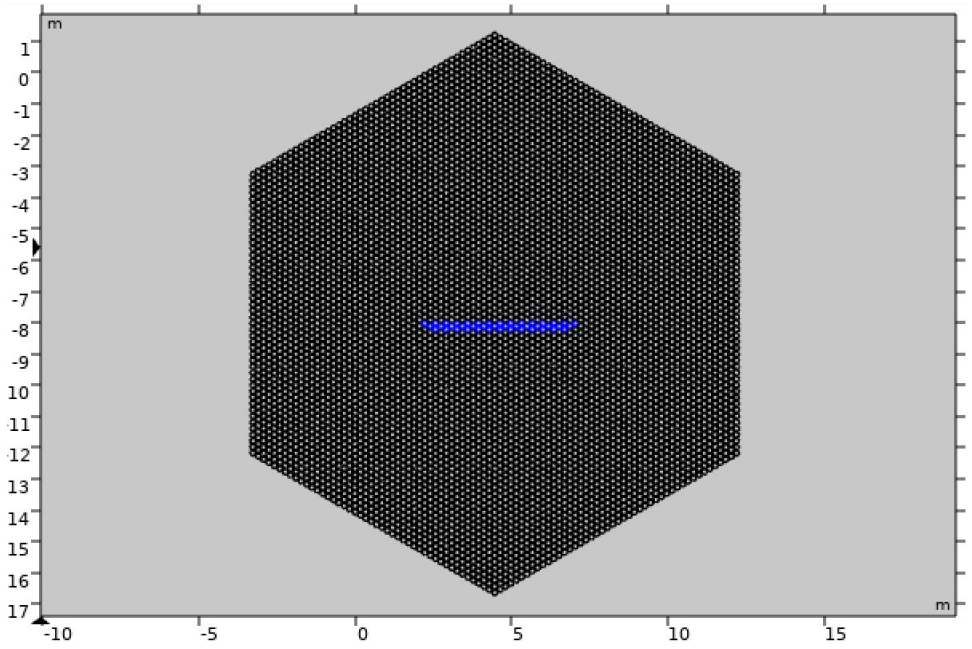

Figure (15): One ideal location within the huddle. The penguins in this location (highlighted in blue) had a body temperature of 38.2°C ± 0.2, the ideal emperor penguin body temperature (Le Maho, 1976).

5.0 Mesh Convergence

The simulation was subsequently performed using the range (2-10) number of edge elements while keeping the "Normal" setting. A mesh convergence analysis was performed at the point (4.42, 1.2) in the model by determining the number of edge elements required for the temperature change at this point to change the least between simulations, ideally remaining constant. Figure 16 shows that a mesh convergence occurs at approximately 6 edge elements, or around 1,673,254 elements total. While the mesh does seem to converge better at 8 edge elements, we limited the simulations to 6 edge elements due to computational time limits. 6 edge elements were chosen for the final simulation as a balance of accuracy and computational time.

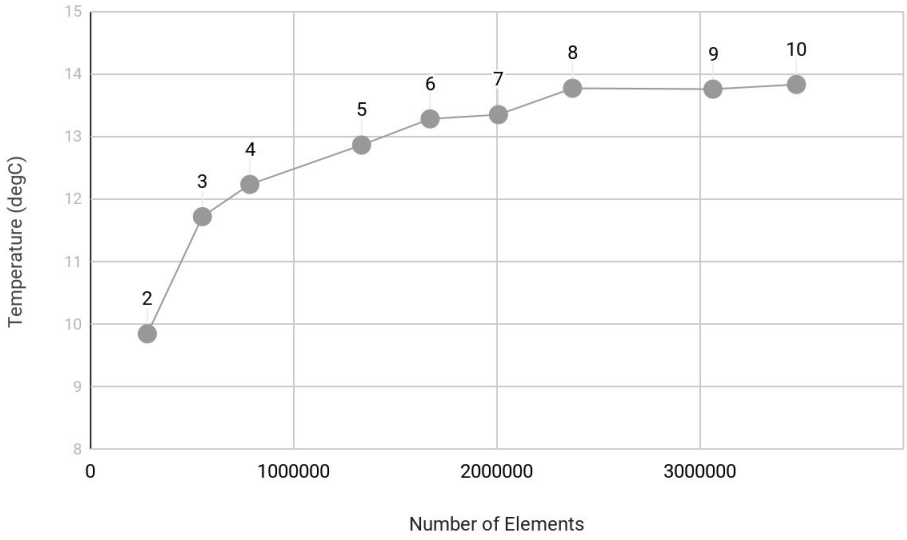

Figure (16): A plot of temperature at point (4.42, 1.2), a point in the penguin core near the boundary with the penguin outer circle. Temperature at the point is used to determine when the mesh converges, which is when edge elements are set to 6. The edge elements value was chosen for the model, as seen in Figure 5, to balance accuracy and computational time.

The solver used was a direct solver for a segregated solution (Figure 17). COMSOL was allowed to choose the default solver method for this computation, which was direct. A segregated solution was used since the temperature change was considered negligible in changing velocity. Therefore, velocity was solved for first, then heat transfer afterwards which saved time in the final computation by reducing the size of the solution matrix. The solver used both MUMPS for fluid flow and PARDISO for heat transfer for the computations.

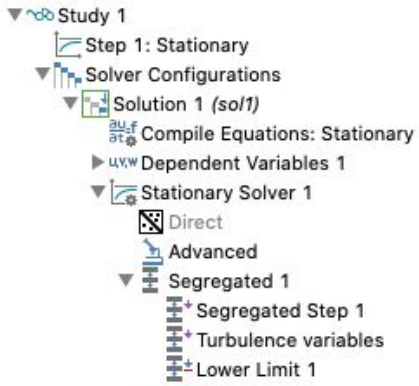

Figure (17): A screenshot of the solver configurations for the model in COMSOL. The segregated tab indicates two separate solutions / solution matrices, and the two “Direct” tabs correspond to fluid flow and heat transfer computations.

6.0 Validation

To validate our model experimental data from Le Maho et. al. 1976 is used for the average body temperature of an emperor penguin. In their experiment, they assumed that the stomach temperature was the core temperature (Le Maho, 1976). The temperature was measured with a thermistor probe that was placed in the stomach of the birds (Le Maho, 1976). Stomach temperature was determined on eight birds during 36 measurements (Le Maho, 1976). The mean temperature for 36 measurements was determined to be 38.2°C (Le Maho, 1976). To see how our model compares, we will use this value of body temperature and compare it to the numerical results of our model. This is shown in Figure 18 below.

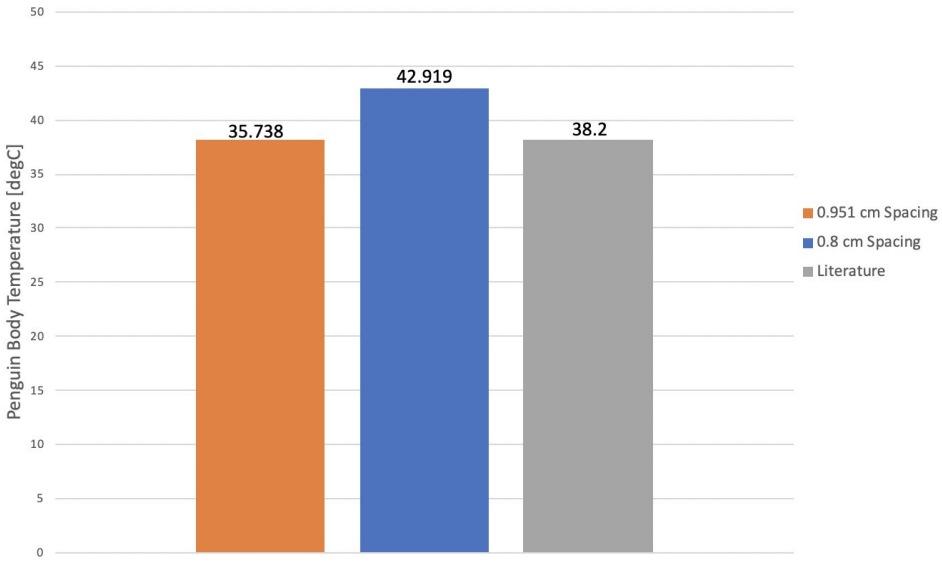

Figure (18): Penguin body temperature validation. This figure shows the comparison between the average body temperature of the penguins in the model (shown in orange and blue, leftmost bars in the graph) vs. the measured stomach temperature used in Le Maho et. al. 1976 (shown in grey, rightmost bar in the graph).

To quantify the difference between these two values and the experimental value, Equation 13 for percent difference is used.

$$\% \, difference = \frac{|V_1 - V_2|}{\frac{V_1 + V_2}{2}} \times 100 \tag{13}$$

From this relation, we find that the percent difference between the 0.951cm spacing and the experimental value is 6.66% and the percent difference between the 0.8cm spacing and the

experimental value is 11.63%. Both of these differences are small when we take into consideration that this model makes several simplifications and assumptions. It shows that our model has penguins with body temperatures that, on average, are physiologically possible. Although the model results are not the same as the experimental ones, they are comparable, and we can confidently say that the ideal spacing is between these two values. Variations may be due to the simplification of thermoregulation made in our model or differences in ambient conditions between what this model uses and the conditions of the measurements taken in the data from Le Maho et. al. 1976.

7.0 Verification

We performed a sensitivity analysis on several parameters to determine how much the numerical solution depends on the values of the parameters used. To do this, a range of possible values was determined for parameters used in our simulation. We want to see how much variation in these parameters would affect the average body temperature of the penguins since this is what our results are based on. The graphs below show the percent change in the generated numerical solution when the parameter was changed to the most extreme value within the range of possible data points.

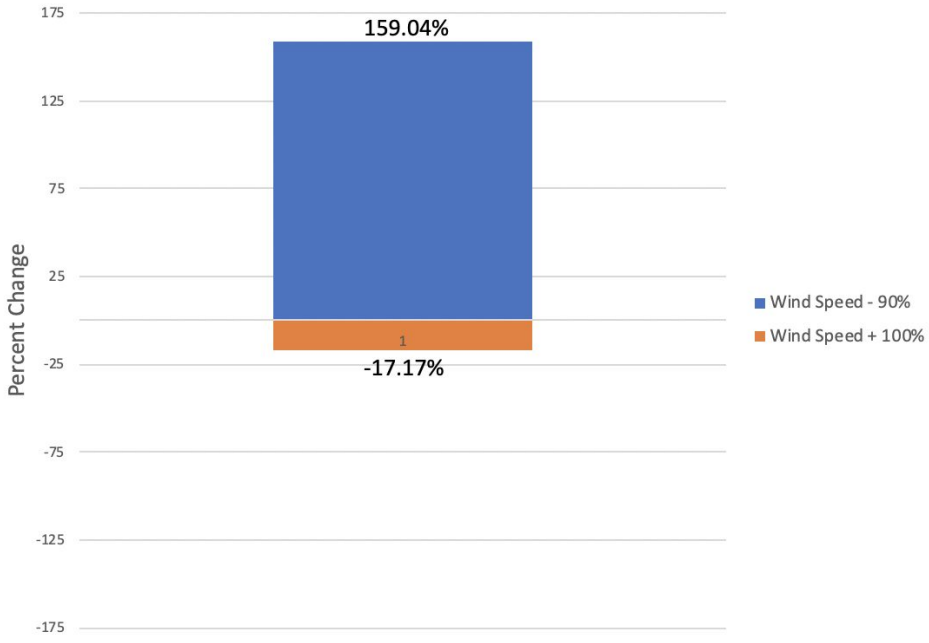

Figure (19): Sensitivity analysis for wind speed at 10 m/s and 1 m/s. The temperature increases a lot when the wind speed is made to be lower. The temperature is less affected by the increase in wind speed.

Figure 19 shows that when the wind speed is decreased from 5 m/s to 1 m/s, it has a large effect on the average body temperature of the penguins. This suggests that wind speed is a large reason why they get so cold. When the wind speed is increased from 5 m/s to 10 m/s, the solution is less affected (although a -17.17% change is still pretty different). This shows that above a certain threshold, the solution will be less affected by an increase in wind speed. We see that it is important to know the exact conditions of the wind being modeled as it affects the average temperature of the penguins by a lot at the extreme ends of wind measured in Antarctica.

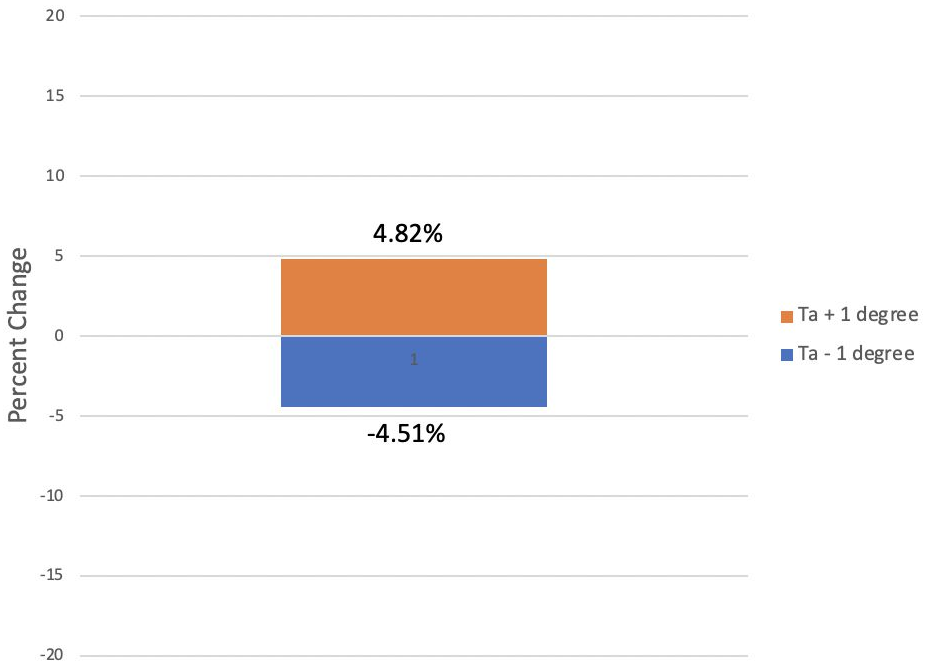

Figure (20): Sensitivity analysis for ambient temperature at -15.5°C and -17.5°C. The average body temperature of penguins changes by over 4% for a 1°C change in temperature.

Figure 20 shows that when ambient temperature fluctuates by a small amount, the huddle body temperature changes by a significant amount. Thus, knowing the exact ambient temperature we are interested in is important (which may fluctuate a little day to day). In relation to global warming, an increase of just one degree warms the average huddle by 4.81%. This would impact the huddle spacing required in addition to how the penguins move within the huddle and could be an important area of future study. Figure 21 shows that C_p does not alter the average penguin body temperature significantly, which assures that the value used for C_p in the model is adequate because these two values represent extreme, almost unrealistic specific heat for a penguin.

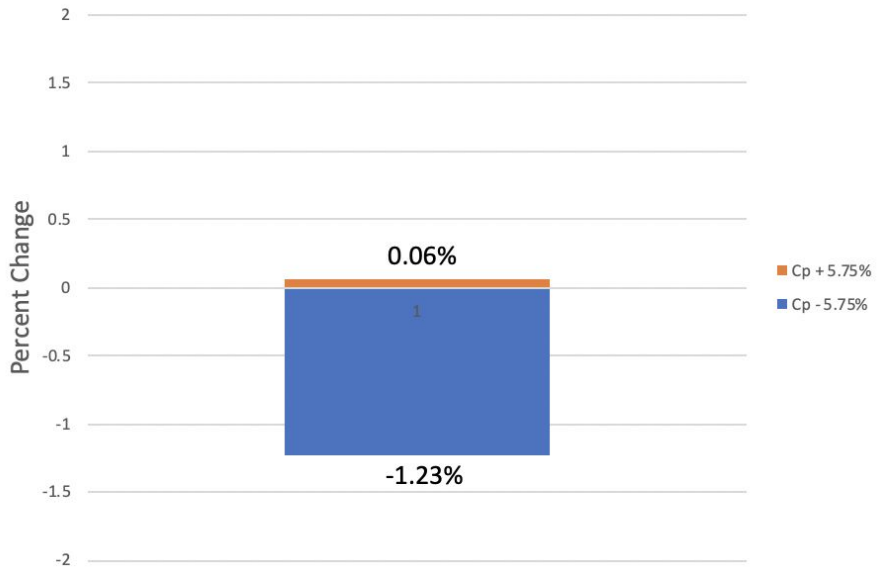

Figure (21): Sensitivity analysis for C_p = 3280J/kg K and C_p = 3680J/kg K. The average penguin body temperature is not significantly affected by this change in Cp.

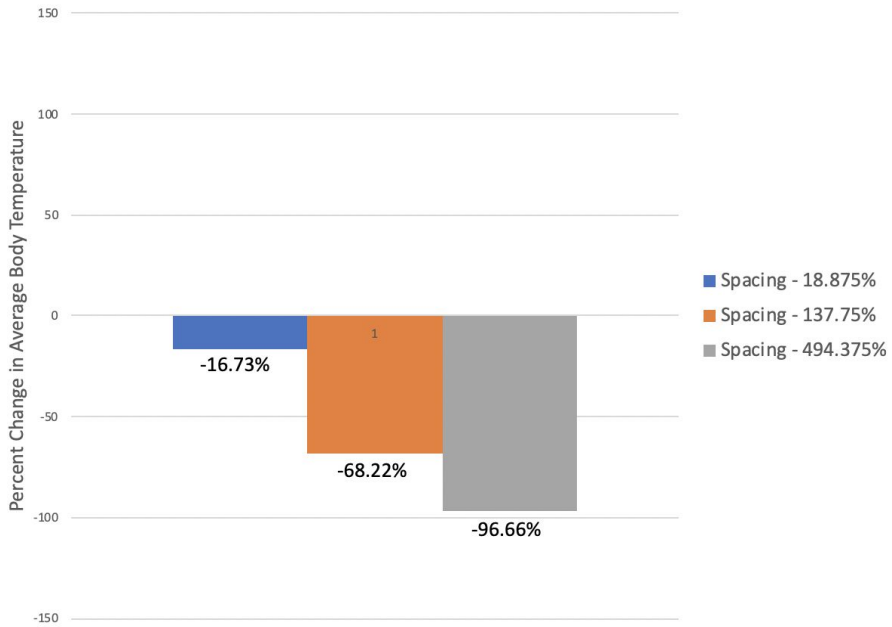

Figure (22): Sensitivity analysis for the spacing between each penguin in the huddle. We see that for smaller changes, a change in spacing can impact the average body temperature by a lot. By changing the spacing from 0.8cm to 0.951cm, the average temperature decreases by about 17%, which is significant. In addition, we see that there is less of a change in temperature between 1.902cm and 4.755cm even though there is more of a change in the spacing itself. When the spacing gets much larger the impact on the overall body temperatures changes less.

One of our research questions (Section 2.2) focused on the ideal spacing for penguin huddles and how much the spacing affects the overall temperature of penguins within the huddle. It is assumed that penguins huddle as close as possible during huddles so our model has a very small value for the spacing between penguins. However, it is important to get a sense of how much a change in this spacing could change the results. In Figure 22, we see that changing the spacing affects the results significantly. However, as the penguins get further and further apart, the spacing changes the results less.

8.0 Conclusions

The results show important data for the ideal spacing of penguins within a huddle and the ideal location to stand within the huddle. Individual emperor penguins would ideally form a penguin huddle between 0.951 cm and 0.800 cm to be warm enough but not overheat. The large variation of temperature in the steady state penguin huddle provides valuable insight into why individual penguins have to move around to regulate body temperatures. Most places within the huddle are either too warm or too cold so the penguins move to regulate their temperature. The warmest spot within the penguin huddle is found to be in the middle, towards the very back. The optimal location within the penguin huddle however, where an individual penguin could maintain an ideal body temperature without moving, is found to be in the middle, slightly to the back.

All this data provides researchers with the reasoning behind why penguin huddles form, how they benefit the penguins, and why penguins move the way they do within the huddles. These conclusions combined with the sensitivity analysis provides further insight into how the conditions in Antarctica may influence penguin huddling behavior. We see that changes in wind speed and ambient temperature can affect the average body temperature of penguins significantly. This would cause a change in behavior as the penguins would have to modify their spacing and patterns of movement to maintain the same body temperature. There are further implications to this and it could be an important and insightful area of further research as conditions in Antarctica continue to change due to global warming. In addition, this model will hopefully provide valuable insight into the penguin heat transfer which will limit the number of in person experiments required to get the same data. This will save money, time, and prevent unnecessary exposure and risk to experimenters.

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10.0 Appendix

10.1 Model Parameters

Used in Numerical Model

Table A1: Parameters used in the model and where in literature they came from. A reference to refer to as we worked.

Air	**Expression**	**Source and Notes**
rho.air	1.57025 (kg/m^3)	From Table C.5. of Basu, P. (2018).
visc.air	146.05E-07 (Pa*s)	From Table C.5. of Basu, P. (2018).
k.air	20.2e-3 (W/(m*K))	From Table C.5. of Basu, P. (2018).
cp.air	1006 (J/(kg*K))	From Table of Gasses of Bejan, A. (2013).
gamma.air	1.4	From COMSOL Material Properties.
T.air	-16.6 (°C)	Average of 7 years from Gilbert, C. et. al. (2007).
u.air	5 (m/s)	Average of 7 years from Gilbert, C. et. al. (2007).

Penguin	**Expression**	**Source and Notes**
number.penguin	6,000 (breeding pairs)	From Le Maho, Y. (1977) and Regel, J. and Putz, K. (1997).
shape	nearly hexagonal	From Zitterbart, P. et. al. (2011) and Waters, A. (2012).
rho.penguin	1015 (kg/m^3)	Assumption rho.penguin=rho.penguin.carcass. rho.penguin.carcass=mass.penguin.carcass/vol.penguin.carcass. mass.penguin.carcass is 23.45[kg], average of 22.2[kg] and 24.7 [kg] from Williams, L. et. al. (2015). vol.penguin.carcass 0.210[m^3] and 0.254[m^3] from Williams, L. et. al. (2015).
mass.penguin	30 (kg)	Average of 20[kg] from Gilbert, C. et. al. (2007) and 40[kg] from Le Maho, Y. (1976).
volume.penguin	0.0284 (m^3)	Volume.penguin=weight.penguin/rho.penguin.

height.penguin	1 (m)	Nationalgeographic.com/animals/birds/e/emperor-penguin.
r.penguin	9.51 (cm)	r.penguin=(volume.penguin/(height.penguin*pi))^0.5
r.feather.penguin	2.2 (cm)	Average of 24[mm] from Du, N. et. al. (2007) and 18[mm] from Taylor, J. R. E. (1986).
T.penguin	40 (°C)	From Le Maho, Y. (1977).
k.feather.penguin	1.725 (W/(m*K))	From Du, N. et. al. (2007). Lacking porosity.
k.penguin	0.0373 (W/(m*K))	k.penguin=k.penguin_m2*(pi*r^2)/d where k.penguin_m2 is an average of 1.6[W/(m^2*K)] and 1.3[W/(m^2*J)] from Le Maho, Y. et. al. (1977)
cp.penguin	3480 (J/(kg*K))	From Schmidt-Nielsen, K. (1997).
Q.penguin	38.7 (W)	From Field Metabolic Rate Equation for loosely grouped penguins in Gilbert, C. et. al. (2007). Field Metabolic Rate Equation for loosely grouped penguins is Q.penguin=rho.penguin*[1.08-(.08*T.air)]+[(0.0092*(weight.penguin^0.66)*(T.air+10)^0.32*u.air^0.5)/weight.penguin]. Around 38.4[W] to 52.6[W] from Le Maho et. al. (1976).

10.2 Result Tables

Used in Figures 13 and 14

Table A2: Temperature and heat flux representation at different huddle locations for a penguin huddle with spacing = r.penguin/12 = 0.80[cm].

Penguin Location	**Temperature (°C)**	**Heat Flux (W/m^2)**
Front	-3.923	-112.11
Middle	35.980	-95.373
Back	70.339	31.899

Table A3: Temperature and heat flux representation at different huddle locations for a penguin huddle with spacing = r.penguin/10 = 0.95[cm].

Penguin Location	**Temperature (°C)**	**Heat Flux (W/m^2)**
Front	-3.968	-82.888
Middle	29.733	-115.76
Back	61.772	31.801

Table A4: Temperature and heat flux representation at different huddle locations for a penguin huddle with spacing = r.penguin/5 = 1.90[cm].

Penguin Location	**Temperature (°C)**	**Heat Flux (W/m^2)**
Front	-4.09	16.14
Middle	10.853	-155.36
Back	41.392	37.254

Table A5: Temperature and heat flux representation at different huddle locations for a penguin huddle with spacing = r.penguin/2 = 4.76 [cm].

Penguin Location	**Temperature (°C)**	**Heat Flux (W/m^2)**
Front	-4.178	186.07
Middle	0.472	-167.88
Back	16.552	40.34

10.3 Numerical Implementation

Figure (A1): The CPU time taken and the memory being used by a typical run of our model.