Case Study

Optimizing BBQs with Conjugate Heat Transfer Simulation in Ansys Discovery Software

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Ansys Software Used

This resource uses Ansys Discovery™ 3D product simulation software

Summary

This case study aims to determine the optimal barbecue (BBQ) accessory configurations for achieving various cooking outcomes. This was prepared for YouTuber "SmokingDadBBQ" and delves into the science behind heat and air flow using both experimental and simulated values based on Ansys Discovery software. It was found that the sloroller conserved more heat by causing the hot air to circulate around the oven interior in a fountain pattern. Conversely, the deflector and pizza stone impeded air flow at the center of the oven, forcing air to escape from the edges. Using the deflector and grill in combination resulted in a similar outcome, but the air escaping through the edges was interrupted by the grill grates, creating little tendrils of air flow. In a configuration including a deflector, a pizza stone, and a grill it was found that a more turbulent airflow at the back of the BBQ is generated. Using only the grill, i.e. a configuration with less obstructions to air flow, the heat rose more steadily through the grates, with more concentration on the center of the BBQ. Overall, the simulation helped to easily and quickly analyze the heat flow patterns which can each be used for different cooking outcomes and to infer design changes to further optimize the BBQ quality.

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1. Introduction

1.1 Fluid Dynamics

Fluid dynamics is an important field of study in engineering. As matter exists in three phases, fluid dynamics considers the motion of both gases and liquids. These concepts are fundamental in many engineering applications. Consider a Formula 1 car's aerodynamics, a blood vessel in the human body or the nozzle at the end of a rocket. An understanding of the dynamics of the fluid medium involved in various scenarios is crucial in engineering problem solving to achieve more efficient energy consumption, lower material and labor costs, and safer industrial and medical operations. As for the context of a BBQ oven, the behavior pattern of heated air within the oven shall be studied as part of this case study to locate the optimal spots to smoke food ingredients.

Figure 1: Examples Involving Fluid Dynamics

1.2 Thermodynamics

Thermodynamics models the heat convection within a defined system or between systems. The study of heat transfer is closely related to people's daily lives as advancements in thermodynamics lead to more efficient utilization of energy. Household appliances such as air conditioners and refrigerators rely on the laws of thermodynamics to function properly. In a BBQ oven, the heat convection between the fuel, the air, and the food ingredients is the most critical factor in determining the overall barbecue quality. The potentially non-uniform heating across the oven interior due to limitations of its mechanical design is researched and discussed.

Figure 2: Examples involving Thermodynamics

2. Concepts

2.1 Convection

Convection is the transfer of heat through the movement of fluids such as gases or liquids. As the barbecue is turned on, it heats over a period of time. When the barbecue is closed, the heat circulates through the air within the barbecue, resulting in convection.

$$Q = hA \, \Delta \, T$$

Equation 1: Convection over Time

- Q = heat transfer rate
- h = convection heat transfer coefficient
- A = exposed surface area
- ΔT = temperature difference

2.2 Heat Flux

Heat flux is the rate of heat transfer per unit area and is typically measured in watts per meter squared (W/m^2). It shows how much thermal energy moves through the surface over time. Heat flux helps determine how much heat actually reaches the food from the heat source. This is useful in determining the proper cooking speed for desired textures and flavors of food. According to Newton's law of cooling, the local heat flux of the object surface can be derived according to the following formula:

$$q = h(T_s - T_a)$$

Equation 2: Heat Flux over Time

- q = heat flux
- h = convection heat transfer coefficient
- T_s = temperature of the object surface
- T_a = temperature of the surroundings ("a" stands for ambient)

2.3 Combustion

Combustion is a chemical reaction that occurs when fuel reacts with an oxidizer. The resultant energy is in the form of heat and light. In the case of the barbecue, coal acts as fuel. Incomplete combustion creates smoke, which gives the food a smoky flavor. Understanding combustion and regulating it though air flow can help achieve the desired flavor outcome.

$$\mathrm{Fuel} + O_2 \rightarrow CO + C + H_2O$$

Equation 3: Incomplete Combustion

3. BBQ

3.1 Purpose

The purpose of this experiment is to investigate how different barbecue accessories affect heat flow, helping to identify the optimal settings for achieving various flavor outcomes.

3.2 Components

A barbecue has a variety of components that are included to change how the barbecue distributes heat, creates turbulence, and positions the substance in which you are cooking. Each of these components will help accomplish a different task when cooking, but more variations of cooking techniques can be created by combining these parts in different configurations.

The individual purpose of each part is:

1. **Grill-** the grill grate is a metal grate that permits air flow through the platform while directly heating up food ingredients resting on it; grill grate creates sear marks on food ingredients and is usually responsible for producing the unique flavor of grilled foods
2. **Pizza Stone**- the pizza stone is a flat slab of ceramic which is in direct contact with unbaked pizza doughs; the pizza stone holds onto heat to allow for thorough heat transfer across the pizza dough
3. **Heat Deflector**- the deflector in the shape of a large solid disk is usually placed right above the heat source and such components play an important role in indirect grilling methods, such as smoking; the deflector redirects the heat away from the food ingredients to allow a gentler heating / smoking process that creates more complexity in food flavor
4. **SloRoller-** the sloroller is a hyperbolic device that deflects and spreads heat more evenly across the oven to improve grilling qualities at lower temperatures; the sloroller helps to bring out more smoking flavor to the food ingredients while reducing the size of hot spots in the oven

4. Experiment Setup

4.1 Materials

For the experimental setup, the following equipment was used:

- Barbecue oven and its appliances
- Charcoal
- Charcoal starter
- Infrared thermal camera
- K-type thermocouple
- Anemometer

4.2 Results

Using the thermocouple and the infrared thermal camera as well as the anemometer, the temperature and the inlet velocities of the BBQ were measured over time starting from ignition.

4.2.1 Temperature

Temperatures were taken at various points in the BBQ using a k-type thermocouple and data acquisition system. An infrared thermal camera was also used for a visual representation of the data.

Figure 3: Experimental setup of the K-type thermocouple and the anemometer (not shown) inserted inside the barbecue (right)

The areas measured include the inlet, outlet, grill, shell, egg, and the ambient temperature. A comparison of these over time has been graphed below.

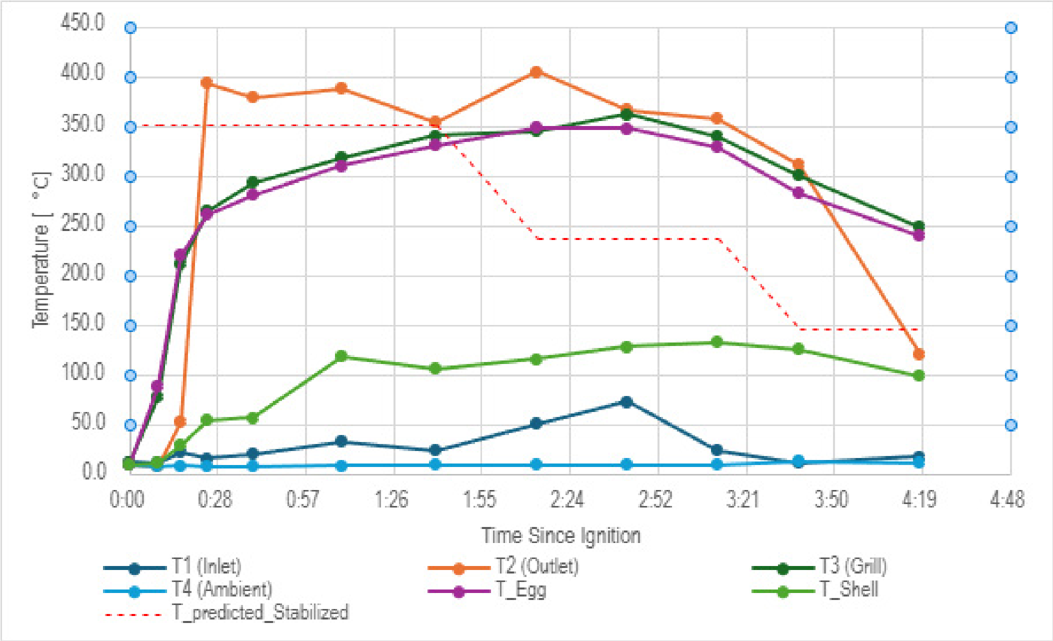

Figure 4: Chart comparing temperatures at points within the BBQ

The inlet and ambient temperatures seem to be very similar throughout, which follows intuition since both are exposed to the exterior environment. Looking at the shell temperature, it steadily heats up over time as the temperature builds within but is still regulated by the outdoor temperatures, leaving the average at approximately 125° C. The egg and grill, both located inside the BBQ, experience much higher temperatures that build up to around 350° C; this is a realistic cooking temperature for most BBQs. Finally, the outlet experiences the most temperature fluctuations. This is likely due to turbulence and air flow recirculation, which can lead to hot and cold areas.

The predicted stabilized temperature is also depicted with a dotted line. Using a weighted average of the mass flow rate between the inlet and outlet, it was estimated that the inlet contributed to 80% of the flow rate while the outlet contributed to 20%. All predicted temperatures were based on this assumption. The estimate started at 352° C and changed to 237.4° C at the 2:13 mark; this is when the inlet was closed to 50% of its area. At the 3:39 mark, the prediction changes again to 145.7° C when the inlet is reduced to 10% of its area. It is important to note that the mass flow rate given the area, velocity, and fluid density was calculated to be 0.0052 kg/s.

4.2.2 Air Velocity

Velocity at the inlet was measured over time using an anemometer. In the simulation, a mass flow rate was specified at the inlet instead of a constant velocity, in order to better replicate realistic conditions. The average velocity over time is shown below. It should be noted that since only the average velocity is measured, this does not represent the full velocity profile.

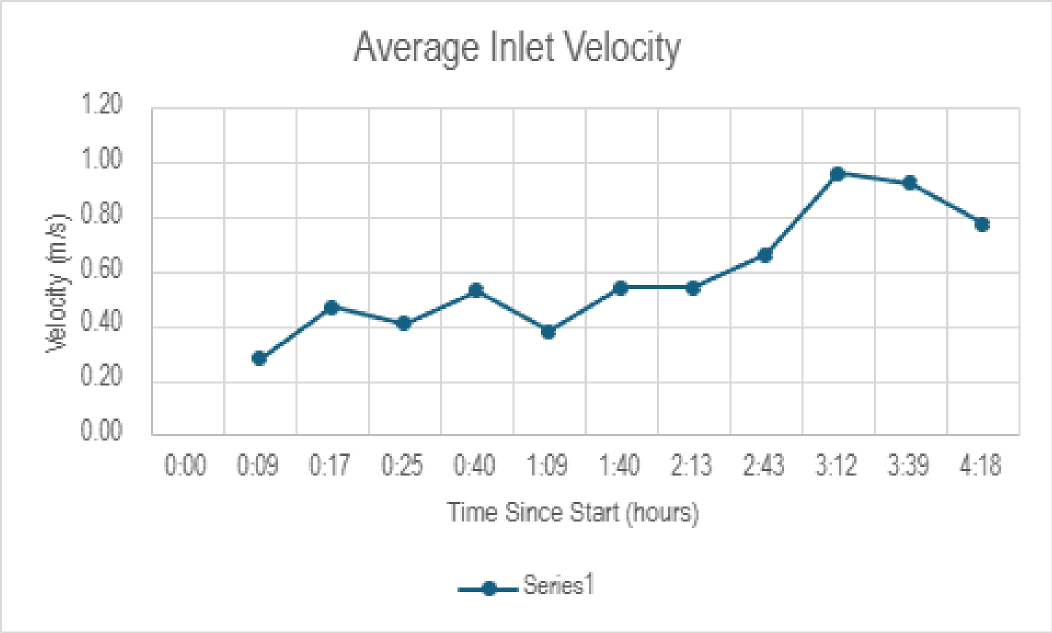

Figure 5: Average Inlet Velocity over Time

The velocity ranges from 0.3 m/s to around 1 m/s, with fluctuations in between. These are likely attributed to environmental factors and area of the inlet over time.

5. Simulation Setup in Ansys

5.1 Materials Setup

To check the material of a component, click on it in the parts tree to the left (click the dropdown arrows if necessary).

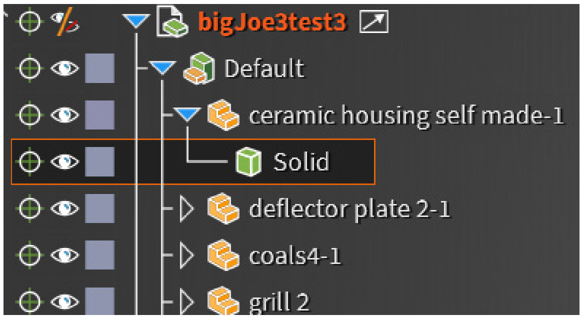

Figure 6: Parts Tree

A material selection box should pop up on the screen. In this case study a new ceramic material was created using the "User defined solid", which is a blank material card that can be used to create your own materials. The material properties of the ceramic for this BBQ are shown in Figure 6.

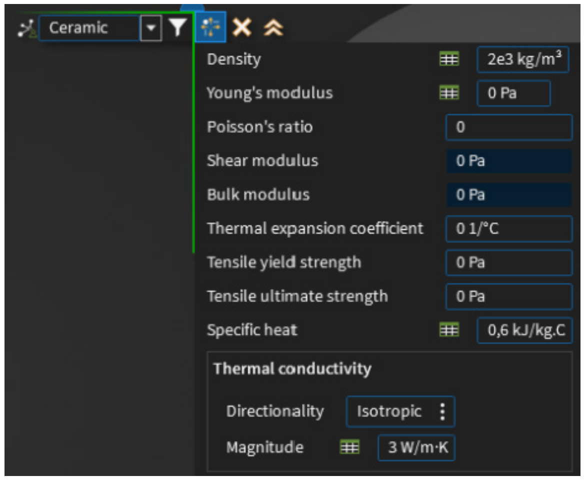

Figure 7: Material Specifications for Ceramic

The parts should show stainless steel for the grills and sloroller, oak wood for the coals, and ceramic for everything else. Both stainless steel and oak wood are predefined materials in Ansys Discovery software's materials library.

5.2 Running Simulation

Step 1: To run the simulation and recreate the below results, the "Explore" must be used. User can click on the left/right arrows at the bottom center to switch between modes.

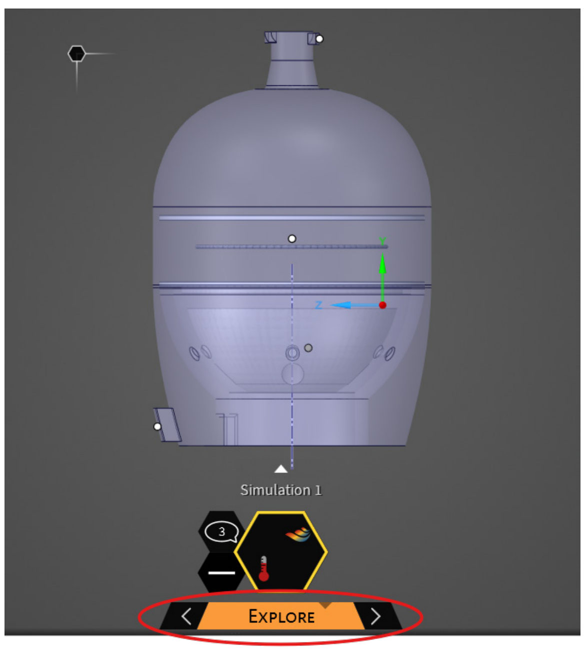

Figure 8: Explore Mode

Step 2: Components that will be included in the simulation can be toggled on and off in the parts tree to the left (refer Figure 9). The eye symbol shows/hides the part from view, and the green target symbol includes/excludes it from the simulation.

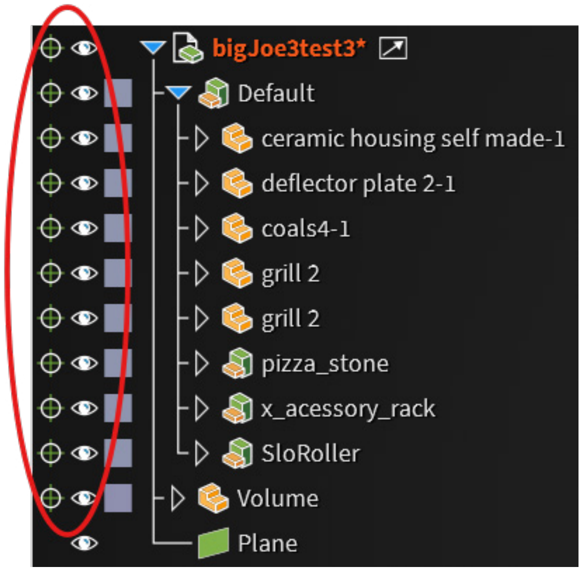

Figure 9: Simulation Parts

Step 3: In order to test different BBQ configurations, the "Update Volume in Context" (Figure 10) was used.

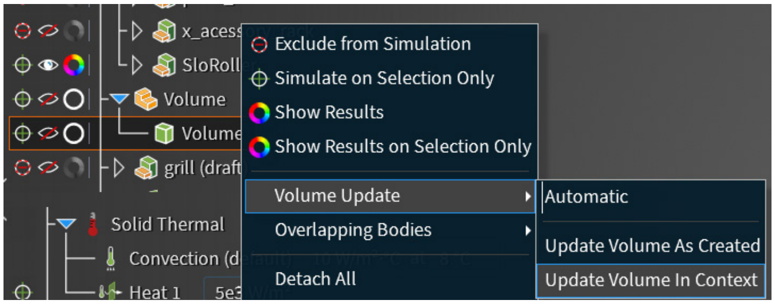

Figure 10: Volume Update

Step 4: The characteristics under the "Physics" dropdown tree on the left should be set up as shown in Figure 11.

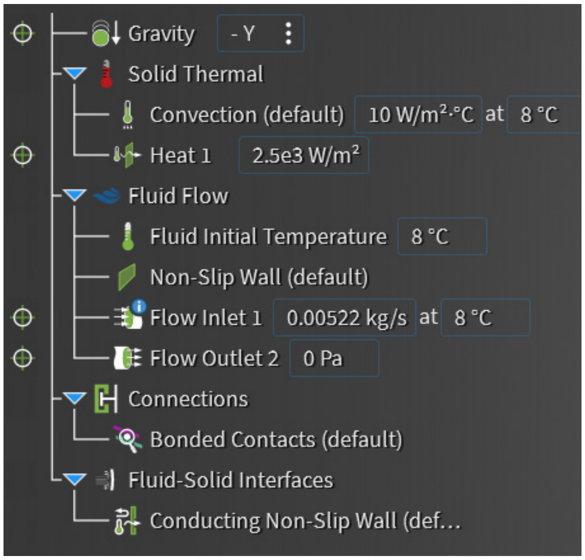

Figure 11: Physics Specifications

Step 5: The following simulation is a steady state simulation (indicated by the horizontal line above the "Explore" tab). One can adjust the fidelity by hovering over the slider in the simulation information display and (Figure 12). Increasing fidelity increases simulation accuracy but also takes longer to run. For the results shown in the following a fidelity of 5.45mm (element edge length) was used.

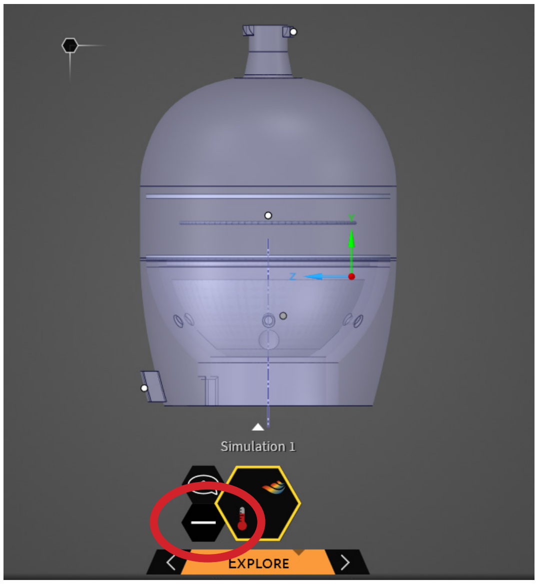

Figure 12: Steady State Mode

Step 6: By clicking the green "power" button in the result arc in the bottom right corner of the screen (Figure 13), the simulation will start.

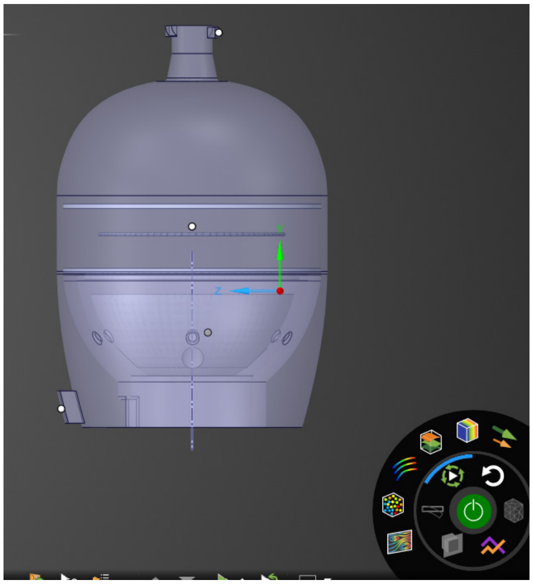

Figure 13: Run Simulation

Step 7: On the color scale to the right, the characteristic state variables may be chosen. The units and increment values can be adjusted on the scale (Figure 14).

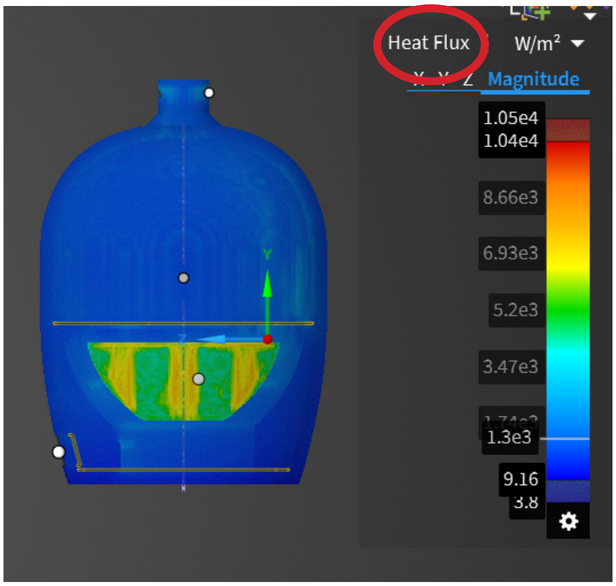

Figure 14: Color Scale Settings

Step 8: In the solve arc (see Figure 15) users can adjust how the state variables should be visualized. The distribution can be displayed through contours, vectors, or other models (hover over each button to learn more).

Figure 15: Simulation Modes

5.3 Geometry Modification

There are 5 main configurations of the BBQ being tested for SmokingDadBBQ. They are as follows:

- Configuration 1: Sloroller and grill
- Configuration 2: Full deflector and pizza stone
- Configuration 3: Full deflector and grill
- Configuration 4: Full deflector and pizza stone and grill
- Configuration 5: Only grill

The purpose is to see how each configuration affects cooking time and which areas of the BBQ become the hottest. This can indicate the optimal settings for each type of food being cooked.

6. Simulation Results and Analysis

6.1 Simulation Result Review

6.1.1 Grill + Sloroller:

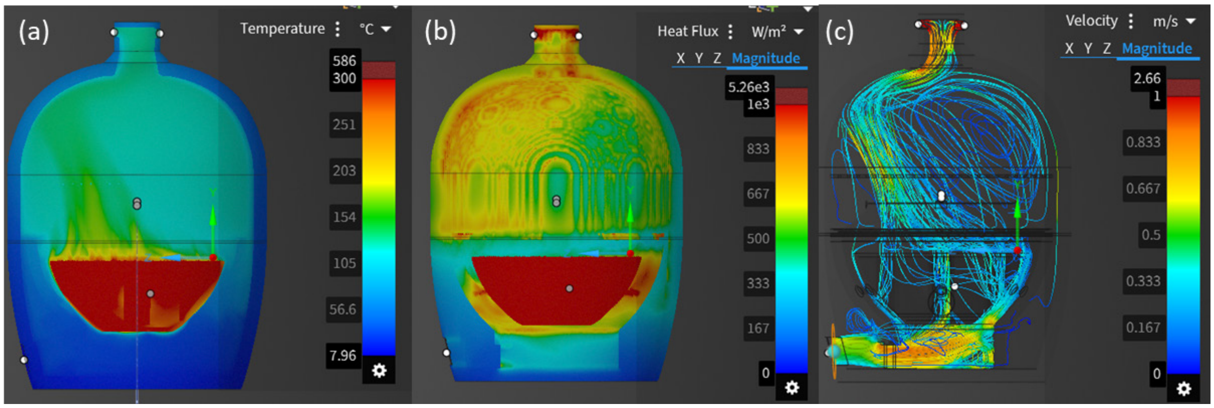

Figure 16: Config. 1 (a) temperature contour plot, (b) heat flux contour plot and (c) velocity streamlines

The sloroller regulates air flow by concentrating air movements to the center of the oven, however the heated air does not immediately leave the oven through the chimney but hits the lid wall instead. The addition of the sloroller conserves more heat by causing hot air to circulate around the oven interior. As shown by Figure 16, the majority of the air flows downward along the walls and starts circulating around the grill grate. As seen from Figure 16, the entire grill grate will reach a uniform temperature upon reaching steady state. However, the simulation shows that the center of the grate will be heated up much faster than other locations.

6.1.2 Full deflector + Pizza stone:

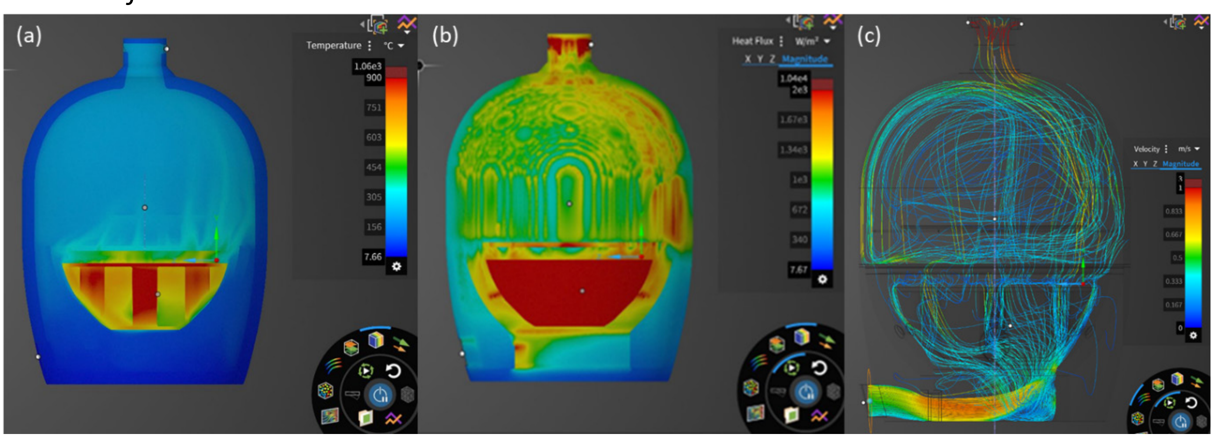

Figure 17: Config. 2 (a) temperature contour plot, (b) heat flux contour plot and (c) velocity streamlines.

The deflector impedes air flow at the center of the oven instead of forcing the air to escape from the edges of the oven, depicted in Figure 17. By treating the air inlet as the front of the oven, it can be regarded that most of the air goes around the deflector from the back side of the oven, which flows along the wall and eventually reaches the front of the oven to form a circulation. The deflector effectively generates a space with lower air temperature and velocity around the pizza stone, but the very back end of the oven is much hotter as it is where the major stream of hot air escapes from the deflector. This can lead to over-baking of the pizza dough near this hot spot.

6.1.3 Full deflector + Grill:

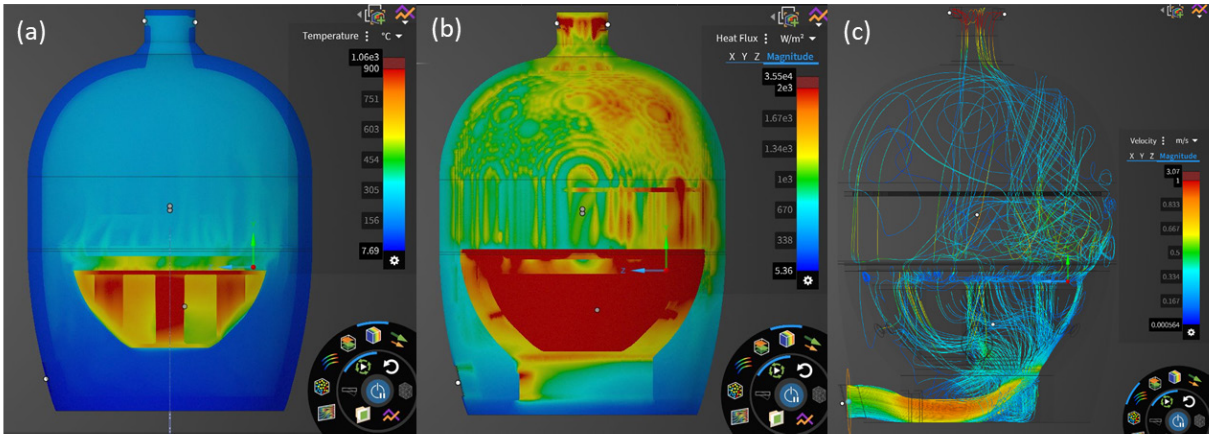

Figure 18: Config 3. (a) temperature contour plot, (b) heat flux contour plot and (c) velocity streamlines.

The deflector impedes air flow and causes most of the air to escape from the back end of the oven similar to configuration 2. However, the presence of the grill grate significantly interrupts the air flow pattern as shown by Figure 18. There is reduced circulation of air established within the oven while a temperature gradient exists between the front half of the oven and the back half of the oven. This temperature gradient can result in non-uniform cooking speed and grilling quality.

6.1.4 Full deflector + Pizza stone + Grill:

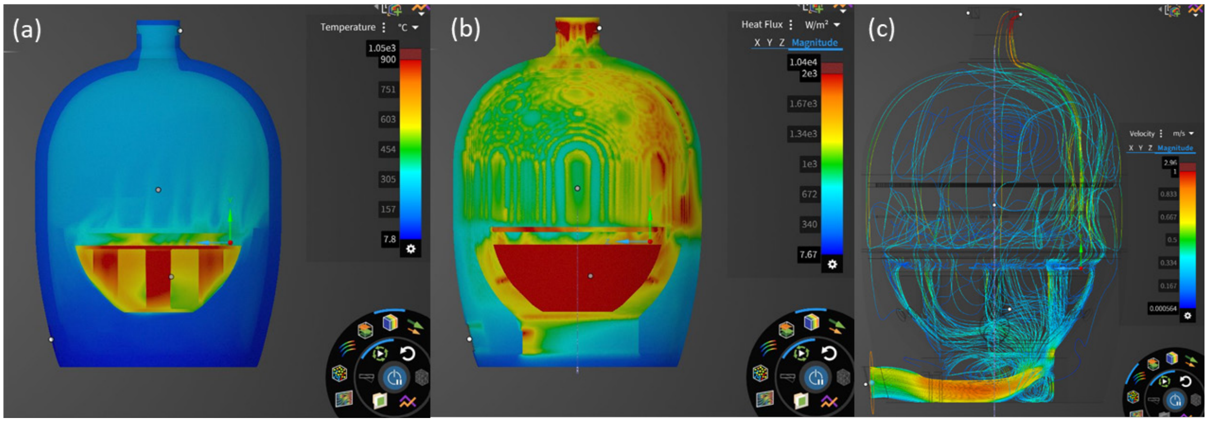

Figure 19: Config. 4 (a) temperature contour plot, (b) heat flux contour plot and (c) velocity streamlines.

The deflector and the pizza stone induce air circulation which is then quickly interrupted by the grill grate. It results in less air circulation compared to configuration 2 despite also having a hot spot at the back of the oven. Additionally, Figure 19 shows that there is active air flow beneath the pizza stone but not above it, which may affect the baking process of pizza doughs.

6.1.5 Grill:

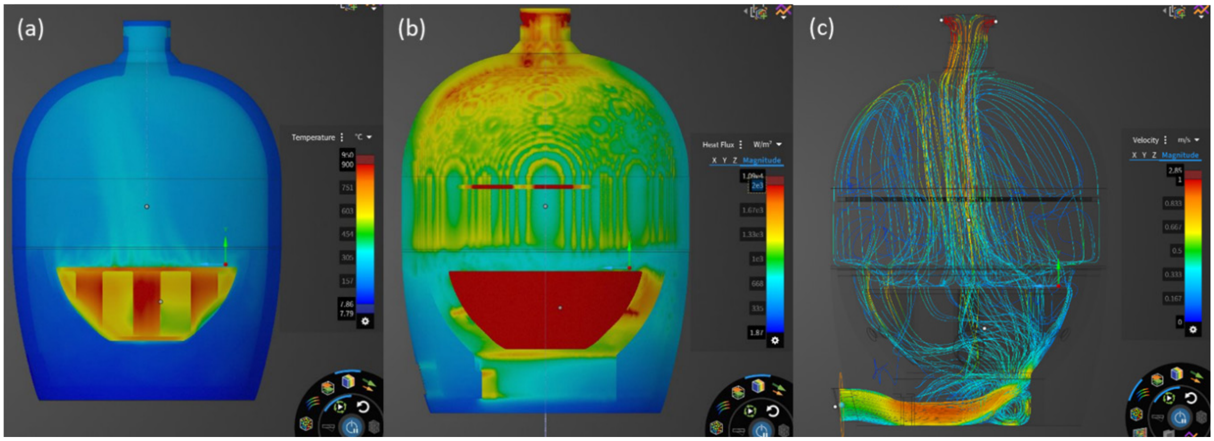

Figure 20: Config. 5 (a) temperature contour plot, (b) heat flux contour plot and (c) velocity streamlines.

The configuration with only the grill grate allows the stream of hot air to travel directly through the grate and reach the chimney. According to Figure 20, the temperature gradient is similar to that of configuration 1 but is less focused to the center. The air circulation behavior is similar to configuration 1 except that more air directly escapes through the chimney rather than forming a circulation. This setup generates a hot spot in the middle of the grate like configuration 1, which may affect grilling quality.

6.2 Sources of Error

6.2.1 Air Leak:

The oven may not be as perfectly sealed as it is simulated in Ansys. The leaked air carries some heat away which can interrupt temperature measurements. Also, turbulence created by the unexpected air flow (e.g. gusts) that happen in the real world (experiment) are not accounted for in the simulation. This potential source of error cannot be resolved as it is part of the mechanical limitations of the apparatus.

6.2.2 Meshing and Fidelity:

The size of fidelity directly influences the quality of simulation, especially in configurations with thin/ tiny features. It must be noted that the maximum fidelity, i.e. mesh size, relies on the individual's hardware performance, specifically the GPU-card. For example, the sloroller and the grill grate may not be recognized properly by the software under a low fidelity setting. As depicted by Figure 21 below, the cross section of the sloroller is disconnected even though it is one single solid piece without any holes when the simulation is run with low fidelity. The air almost freely passes through the sloroller and the grill grate boundaries with minimal interference. On the other hand, the sloroller is properly recognized as one solid piece with high fidelity setting, and the velocity plot now clearly reflects the grill grate and the sloroller's impact on the fluid behavior.

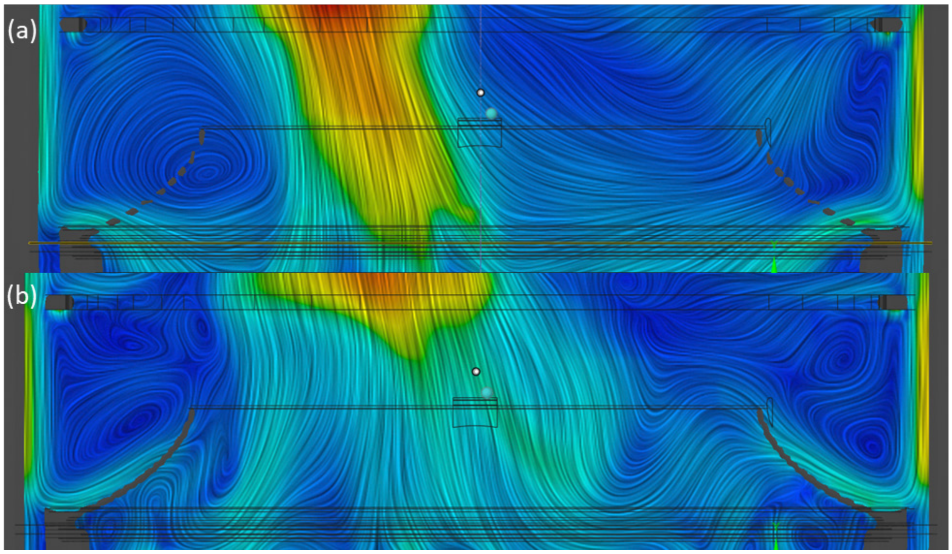

Figure 21: Air Velocity Near Sloroller and Grill Under (a) Low Fidelity and (b) High Fidelity.

6.2.3 *Refine Mode:*

When switching from Ansys Discovery software's GPU-based solver in the Explore Mode to the CPU-based solver in the Refine Mode, a more precise simulation results can be produced at the expense of high run times.

6.2.4 *Turbulence Model:*

Different types of turbulence model used in solving a computational fluid dynamic (CFD) problem can significantly impact the precision of the simulation. Models with less computational cost often yield less accurate simulations, but there are context-specific exceptions. Ansys Discovery software can switch between three models for CFD simulations, which are laminar, turbulent k-omega SST, and Smagorinsky (LES). The laminar model neglects most of the turbulence in fluid movements and thus is the least favorable model for this application. The LES is relatively more accurate in solving large turbulence structures, but it requires significantly more computational power and cannot accurately capture the effect of boundary layers. On the other hand, the k-omega SST model is much better at handling near wall conditions while being more energy efficient than LES [1]. In general, k-omega SST is still the optimal model for the Conjugate Heat Transfer simulation of the BBQ oven with Ansys Discovery software despite its limitations.

7. Conclusions

In conclusion, the 5 configurations offered various heat flow patterns which can each be used for different cooking outcomes. The Ansys simulation values provided insight on air flow and temperature over time, while the experimental values gave a realistic example of what a BBQ would experience when exposed to environmental factors and helped qualitatively verify the simulation. Minor discrepancies between the two methods were likely attributed to air leaks, meshing and fidelity, or turbulence. The case study has shown how Ansys Discovery software can be used to run a conjugate heat transfer simulation to understand and subsequently optimize a BBQ design.

8. References

[1] https://www.engineering.com/choosing-the-right-turbulence-model-for-your-cfd-simulation/

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