Real-time Low-Resolution Heat Flow Simulations for Cleaner Combustion of Biomass

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Problem description

Improved cooking stoves with reduced fuel consumption and improved thermal performance have received little attention using advance technology and CFD modelling.

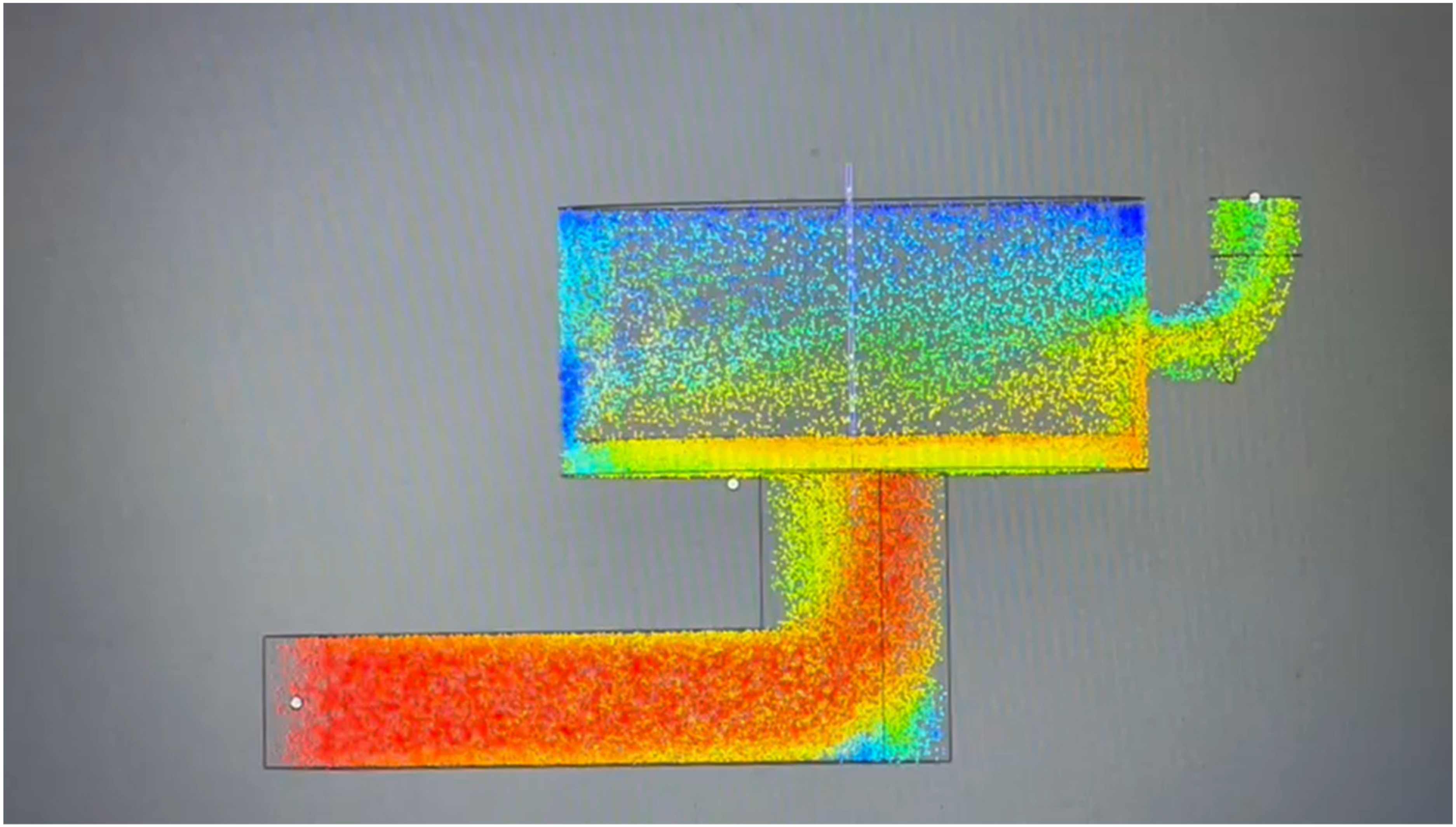
This presentation is about the development of significant improvements made using a low-resolution CFD modelling package from ANSYS called Discovery Enterprise. Two new products were developed:
A 500 litre cooking stove for Rwanda and a 650 litre distillation stove for rural Madagascar.

Improved Stoves in Africa

For more than 20 years modest improvements have been made over traditional appliances and categorized as “improved stoves”. None of them are close to being optimal in large part because they were developed by accumulated experience and “guessing”.

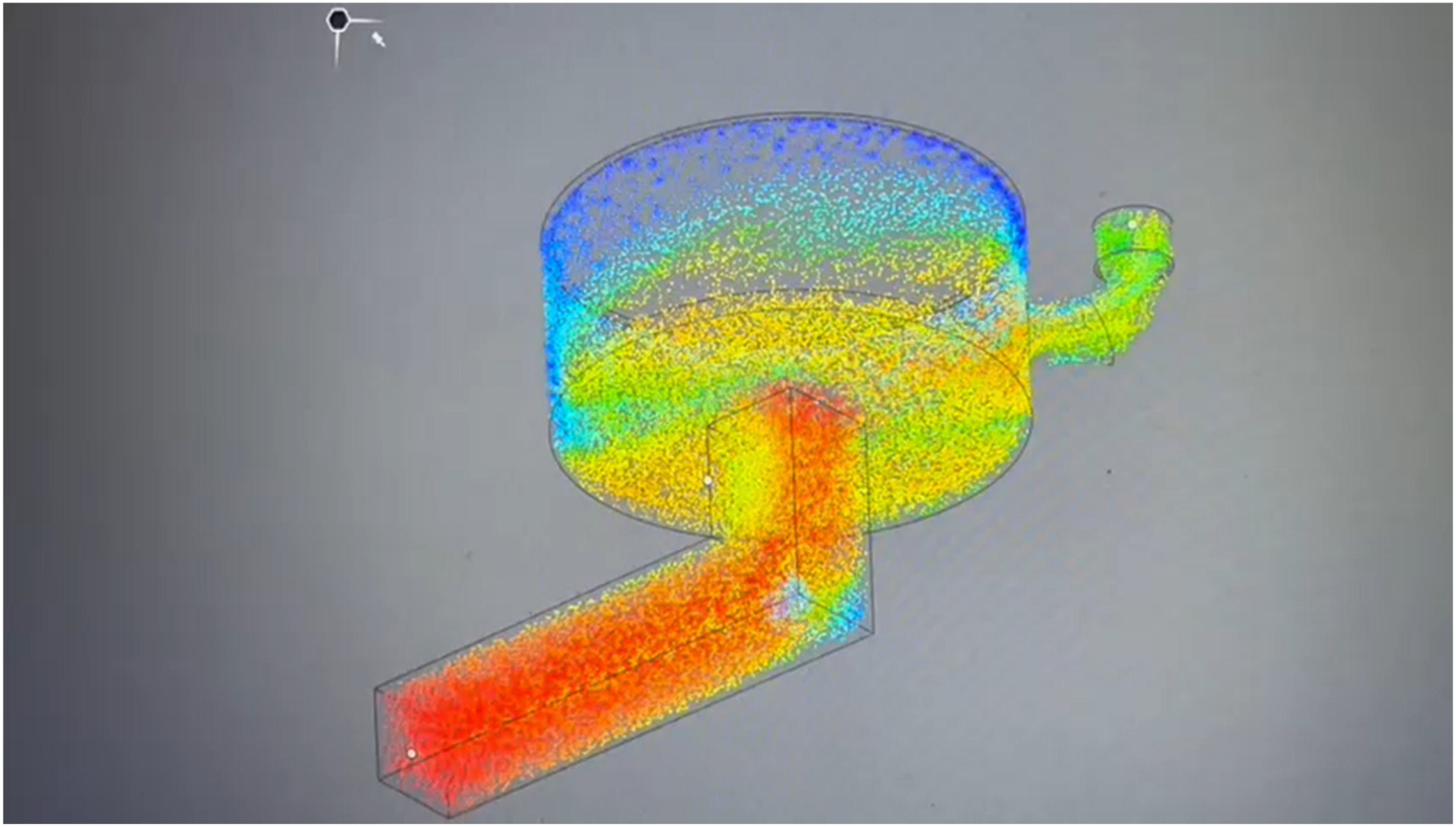
Discover Enterprise from ANSYS

This is the heat flow modelled on the stove just shown. The pot is heated strongly in the centre and much of the heat goes directly to the chimney. The front of the pot is barely heated at all.



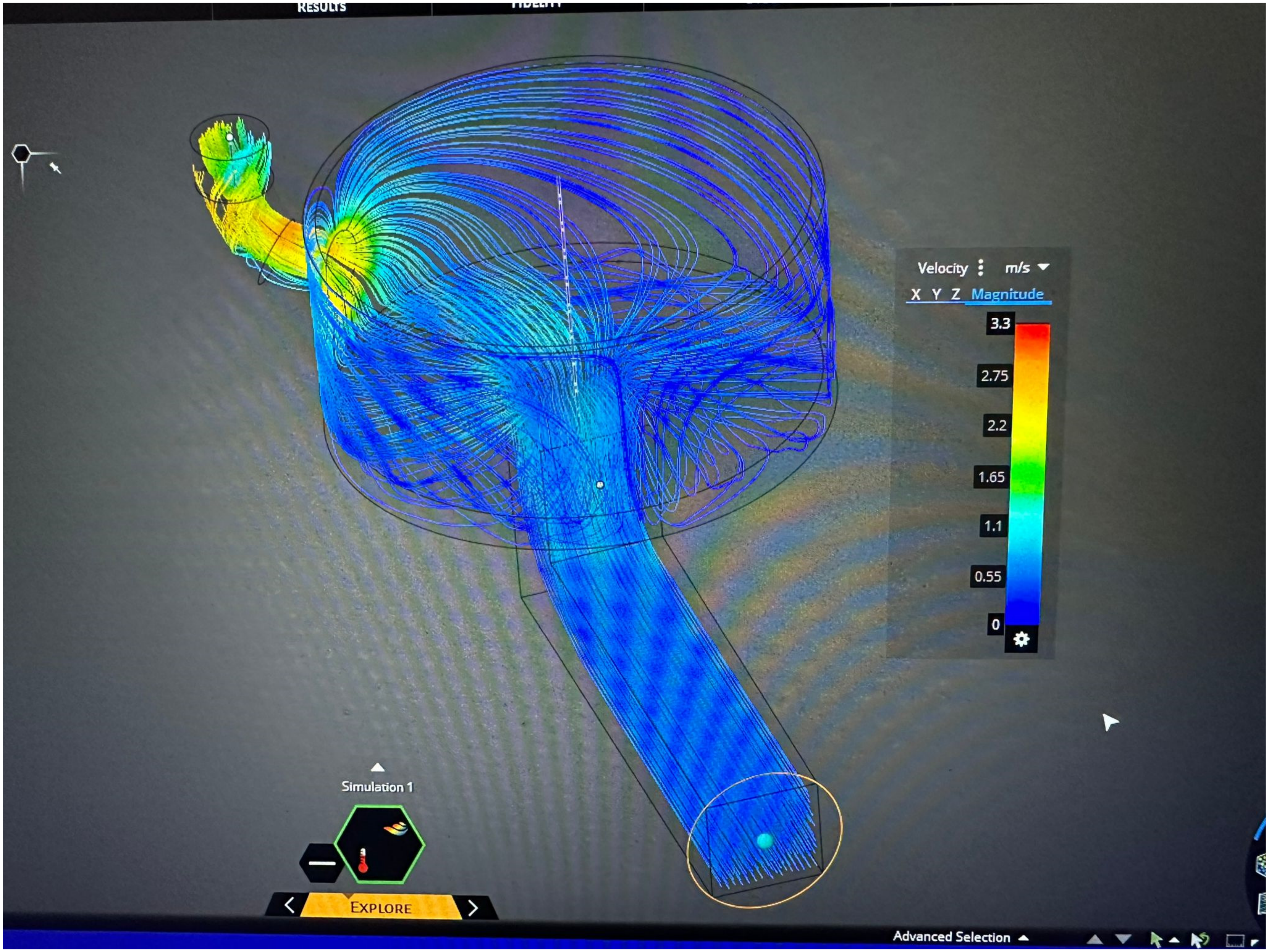
Discover Enterprise from ANSYS

This is the same stove seen from below. Notice the cold zone at the bottom corner of the combustion chamber. Unburned charcoal accumulates there.



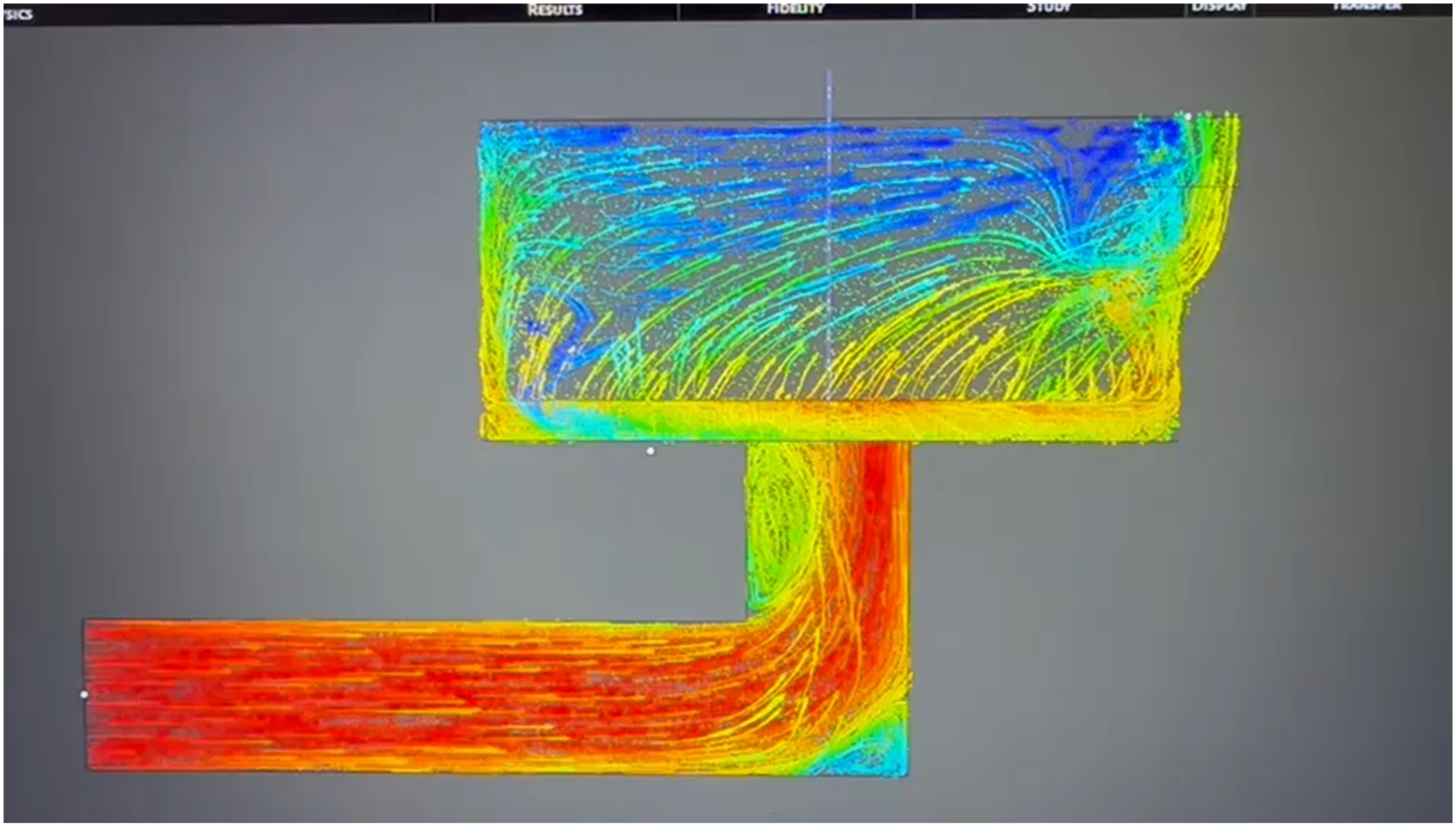
Discover Enterprise from ANSYS

The simulation can display velocity using coloured streamlines.



Discover Enterprise from ANSYS

Combining the flow and streamlines often gives the best understanding. We observe that the majority of the heat is directed against the back wall of the combustion chamber, destroying even stainless steel and refractory materials.



Kabuga Stove v3.0

The first thing to do is to add a grate under the combustion chamber to bring primary air to burn the charcoal which accumulates against the back wall.

This white grate is made from cast refractory material because steel grates were being destroyed in 10-14 days.

The four stands are to support a heat diffuser plate.

Kabuga Stove v3.0

This is the first diffuser plated tested in the field. It is made from 12mm mild steel plate.

The area of the holes is 5.5% of the total area of the 600mm diameter disc.

The holes together pass only 15% of the heat from the fire to the area of the pot immediately above the diffuser.

This prevents the Leidenfrost Effect (boiling catastrophe) from damaging the pot.

Kabuga Stove v3.0

This shows the diffuser plate being placed on its 4 supports.

The diameter of the plate is 600 mm. The diameter of the pot is 1.1 metres.

The clearance between the pot and the cylindrical stove body is 45mm. The vanes could be added to the masonry walls, but it is easier to weld them to the pot.

Preparing to test the KB 3.0

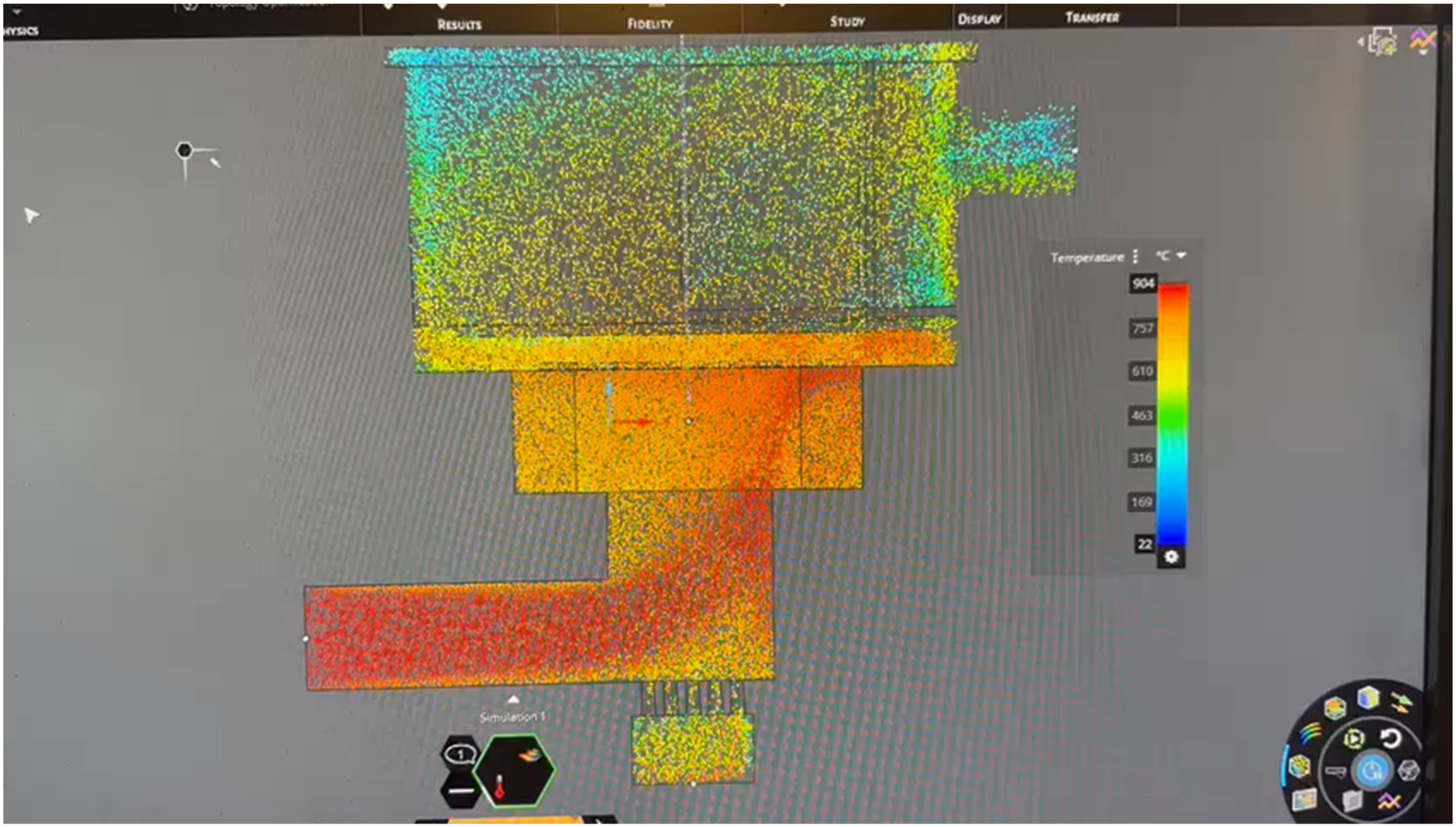
The pot is difficult to handle, as it weighs over 60 kg. The orientation of the pot makes no difference to the thermal performance.

Preparing to test the KB 3.0

This stove boiled 420 litres of water in 70 minutes with a 72 kW fire.

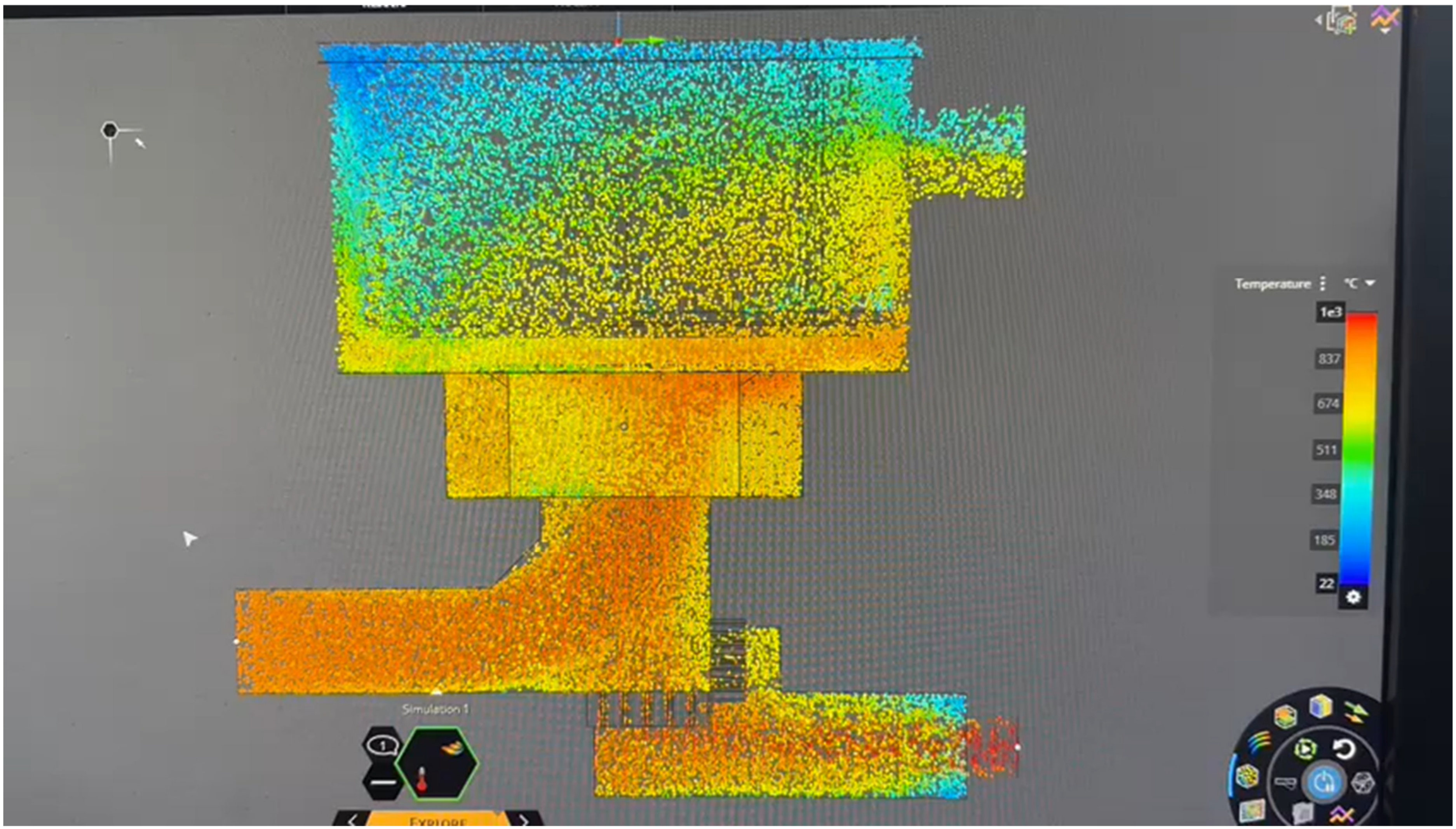
Testing the model, Version 3.

This version has a diffuser plate to spread the heat over the bottom of the pot, and 4 vanes to block the hot gas's direct access to the chimney. Note that the hottest gases are still directed against the back wall, but the general heat distribution is much better.



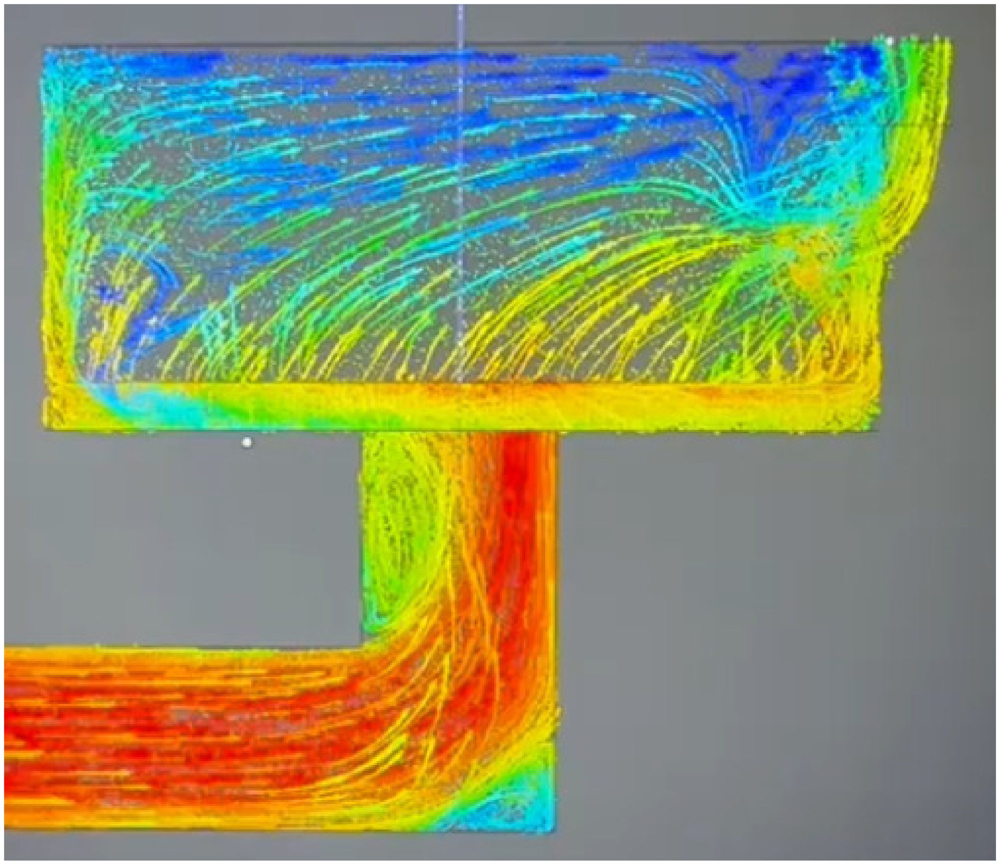
Testing the model, Version 3.

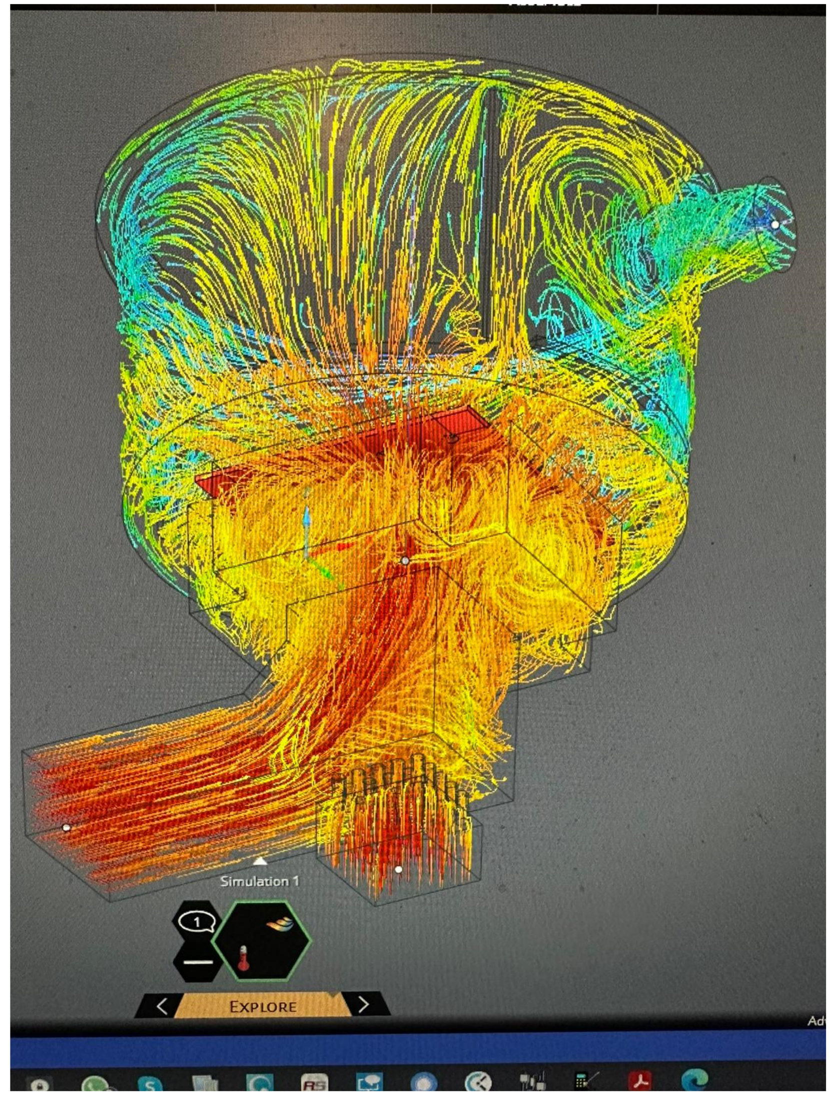
A second grate was added with primary air coming from behind the fuel, and a bevel was cut into the upper surface of the fuel tunnel. This greatly reduced the heating of the back wall of the combustion chamber.



Testing the model, Version 4.

This is a view from below showing that the streamlines are very different from the original Rocket Stove. The diffuser plate is now square because the brick masons had difficulty creating a conical expansion zone above the combustion chamber.





Before

After ➔

Testing the model, Versions 4 and 4.1.

Two versions of this stove were constructed, with 4.1 having a combustion chamber lined with replaceable plates made from local volcanic rock. The average thermal efficiency while cooking fired with 14% moisture fuel is 60%. Maximum firepower is 72 kW.

The only difference: v3.0 (left) has a round diffuser plate and 4.x has a square diffuser plate.

Clove oil distillation in rural Madagascar

This is a photo of a primitive clove oil distillation unit in a remote area of Madagascar, an island country in the Indian Ocean.

The lower portion of the pot is heated while the top is protected from heat. This is because it is filled to the top with biomass that has to be steamed. There is water only in the lower 40% of the pot volume.

Only the boiler is shown in this photo. The steam collection hood and condenser has been removed.

Clove oil distillation in rural Madagascar

This can be considered an "improved clove oil distiller".

The bottom door is the ash cleanout.

The top door is for feeding in fuel.

The cap collects the evaporated water and oil.

The pipe conveys the steam to the condenser. The oil is separated by flotation, and the water is returned to the boiler.

This same system is widely used to make ethanol fuel.

Clove oil distillation in rural Madagascar

The experience gained developing the Kabuga Stove 4.x in Rwanda was only partially relevant.

Because the upper part of the pot is not to be heated, a higher surface area was created by modelling vee-shapes into the pot bottom increasing the surface area by more than 30%.

The vanes welded onto the outside of the KB 4.x were added to solve the same fire-to-exit gas path problem.

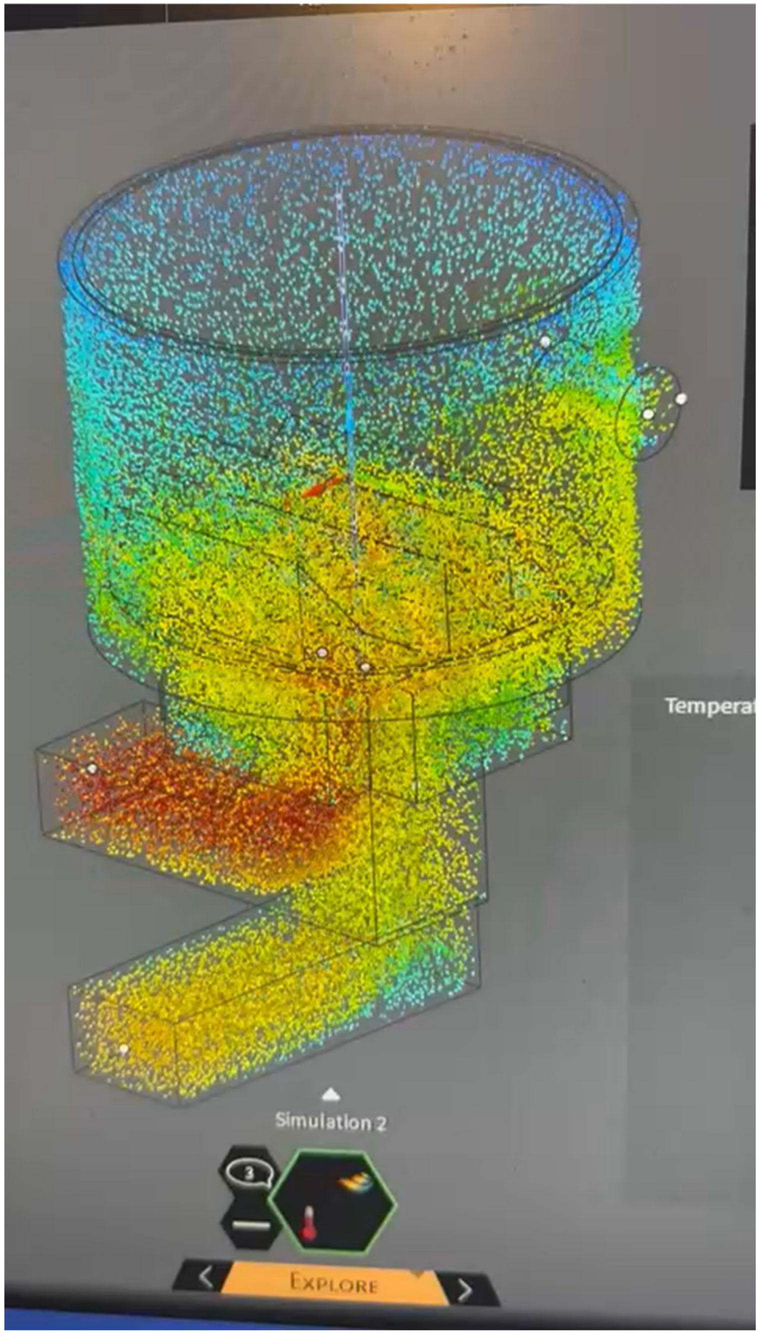
As with the KB 4.x the pot has to be oriented correctly: here the front is shown and the chimney is at the back. The pot should be placed within 10 degrees of this position. The lifting handles can be used to indicate its orientation.

Clove oil distillation in rural Madagascar

The first models were created with the vees in the pot bottom, a diffuser plate as with the KB stoves, and no vanes.

This model was made to demonstrate the different between adding vee grooves underneath, or not. They were expected to have a strong effect on the gas flow direction, with and without vanes, so both were simulated.

As the diffuser is quite expensive, it was also tested with and without that component.

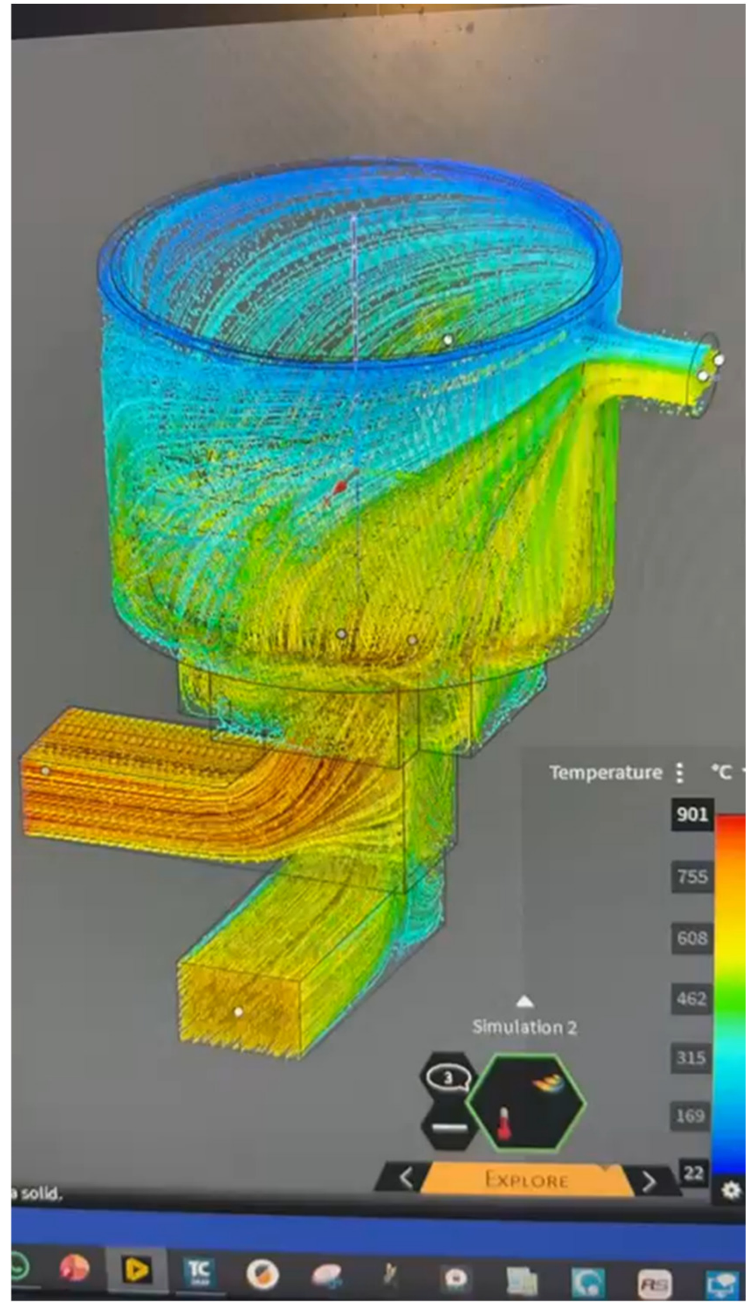


Clove oil distillation in rural Madagascar

As before, it was run with the streamlines displayed to get a good understanding of where the flow went, and at what temperature.

It can be seen that the front of the pot receives little heat as there is little flow there.

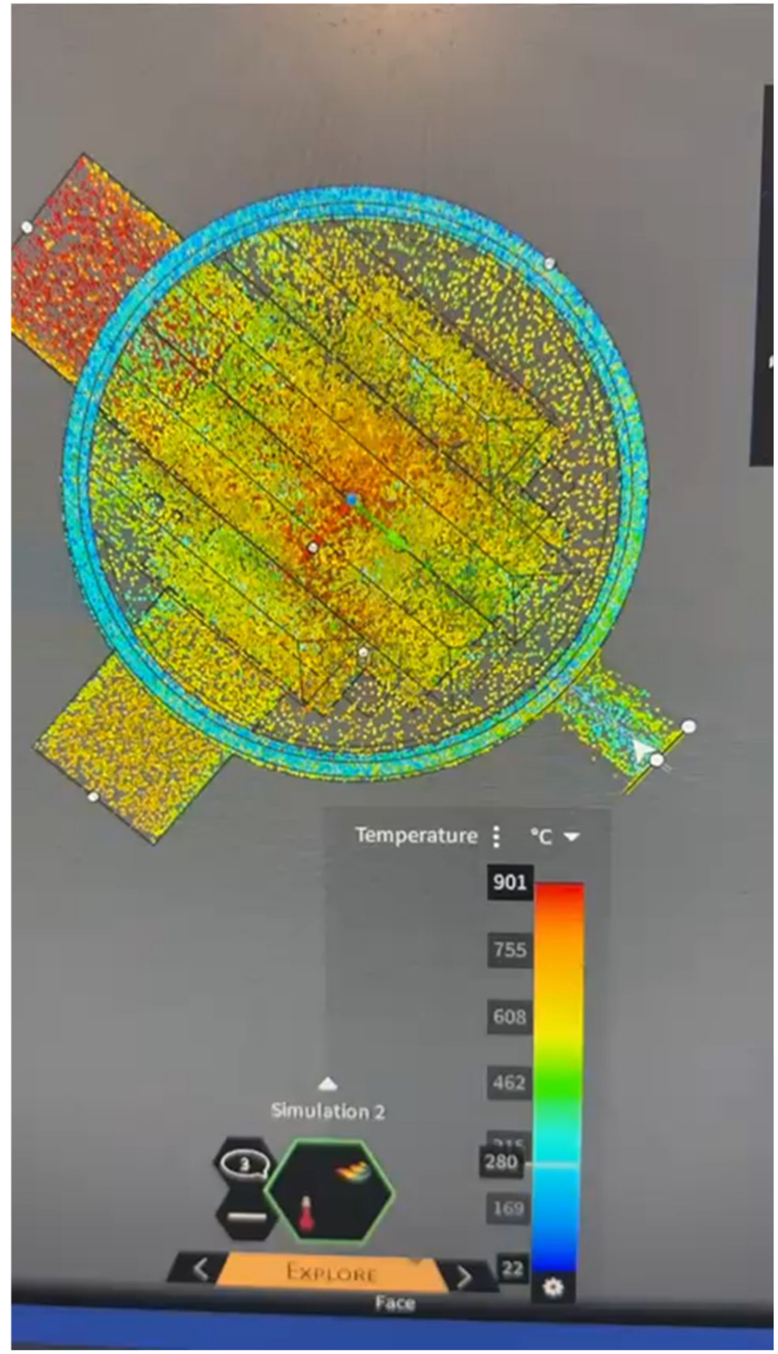
There is a strong vertical disparity in the heat flow into the chimney, cold on top and hot on the bottom.



Clove oil distillation in rural Madagascar

Seen from above, the flow looks relatively even, but this is deceptive.

The hot gases are escaping from the combustion chamber and going to the chimney as directly as they can.



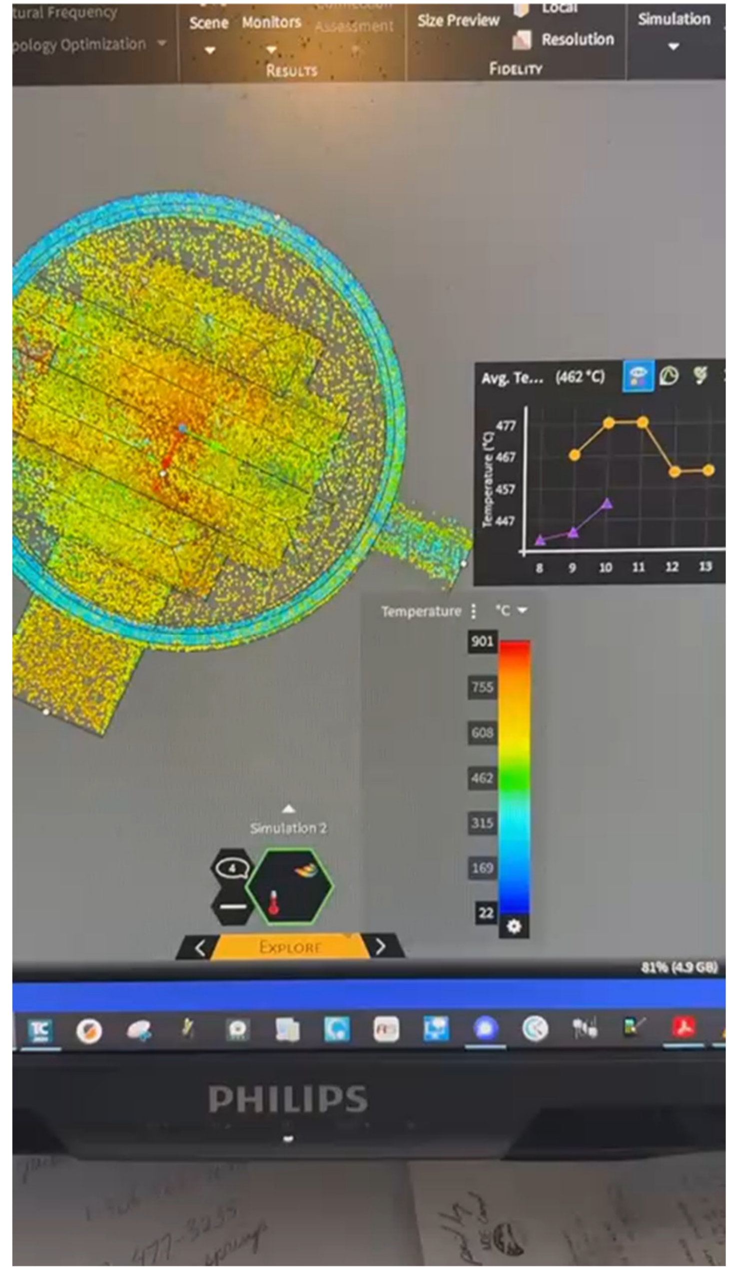
Clove oil distillation in rural Madagascar

Next, the diffuser was removed from the simulation.

The result was nearly identical, showing there was no value to having it.

The vee channels dominate the direction of the gas flow.

The chart on the right is a “Monitor”. Each successive run has a new data point plotted. It shows that, with or without the diffuser, the gas exit temperature is the same at 462° C.

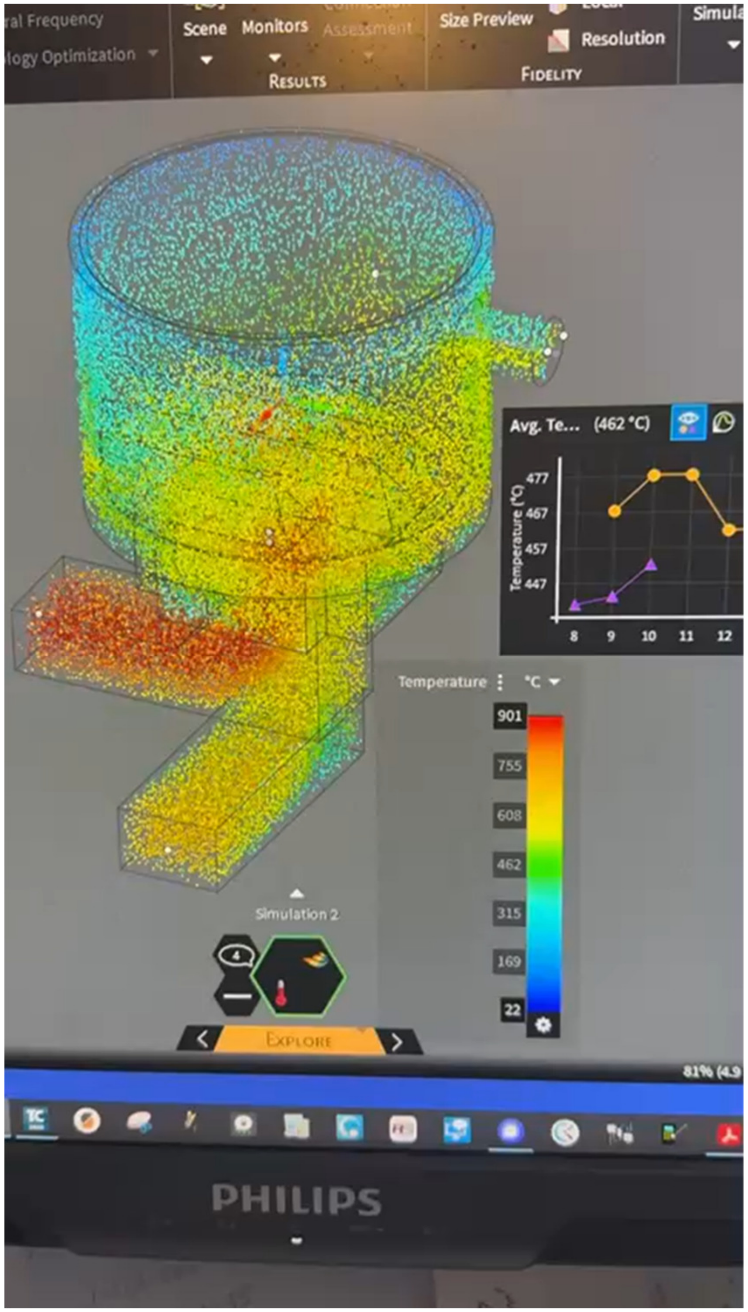


Clove oil distillation in rural Madagascar

Seen from the side, some differences can be noted when comparing it with the original Rocket Stove layout.

The primary air coming under the grate, even though it is from the side, keeps the hottest gases away from the back wall of the combustion chamber.

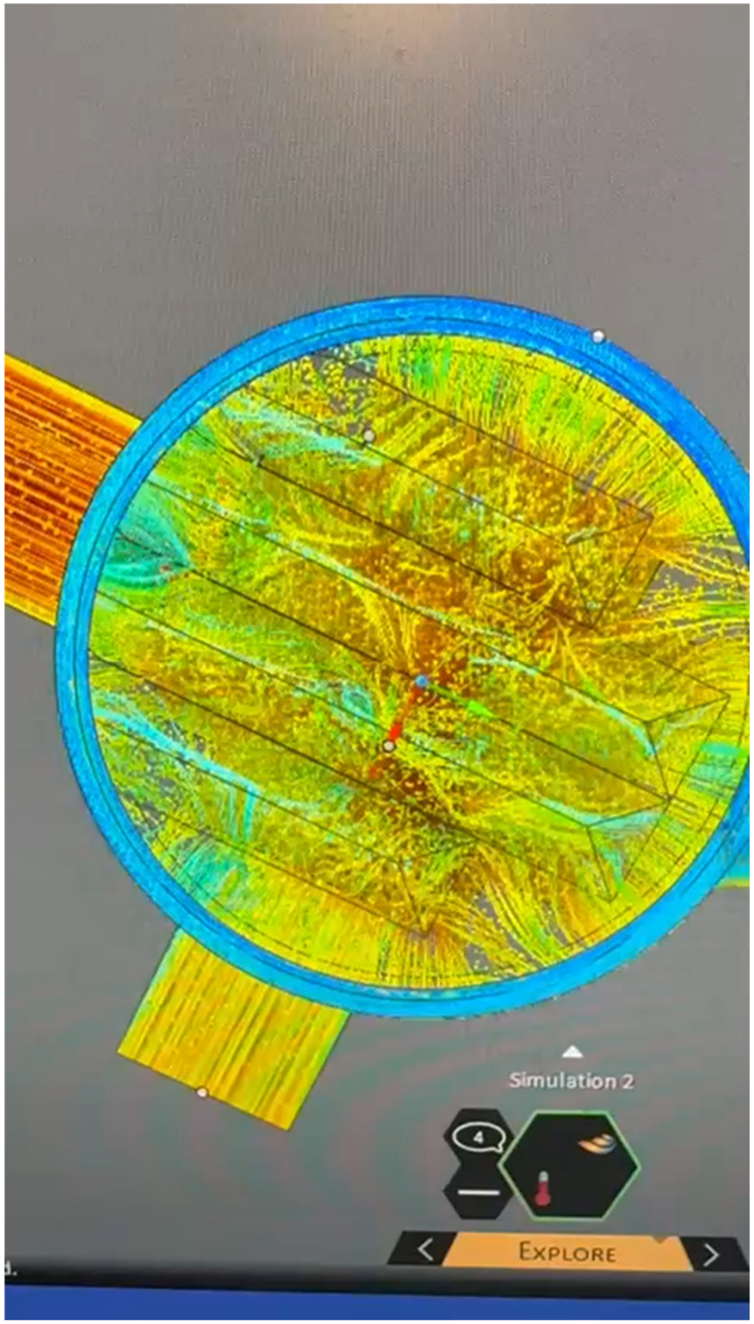
With no diffuser, the vees dominate the gas flow direction and are doing a good job of breaking up the concentrated heat that would otherwise be applied to the centre of the pot.



Clove oil distillation in rural Madagascar

Overhead view:

Streamlines add clarity. The vee channels are distributing heat well.

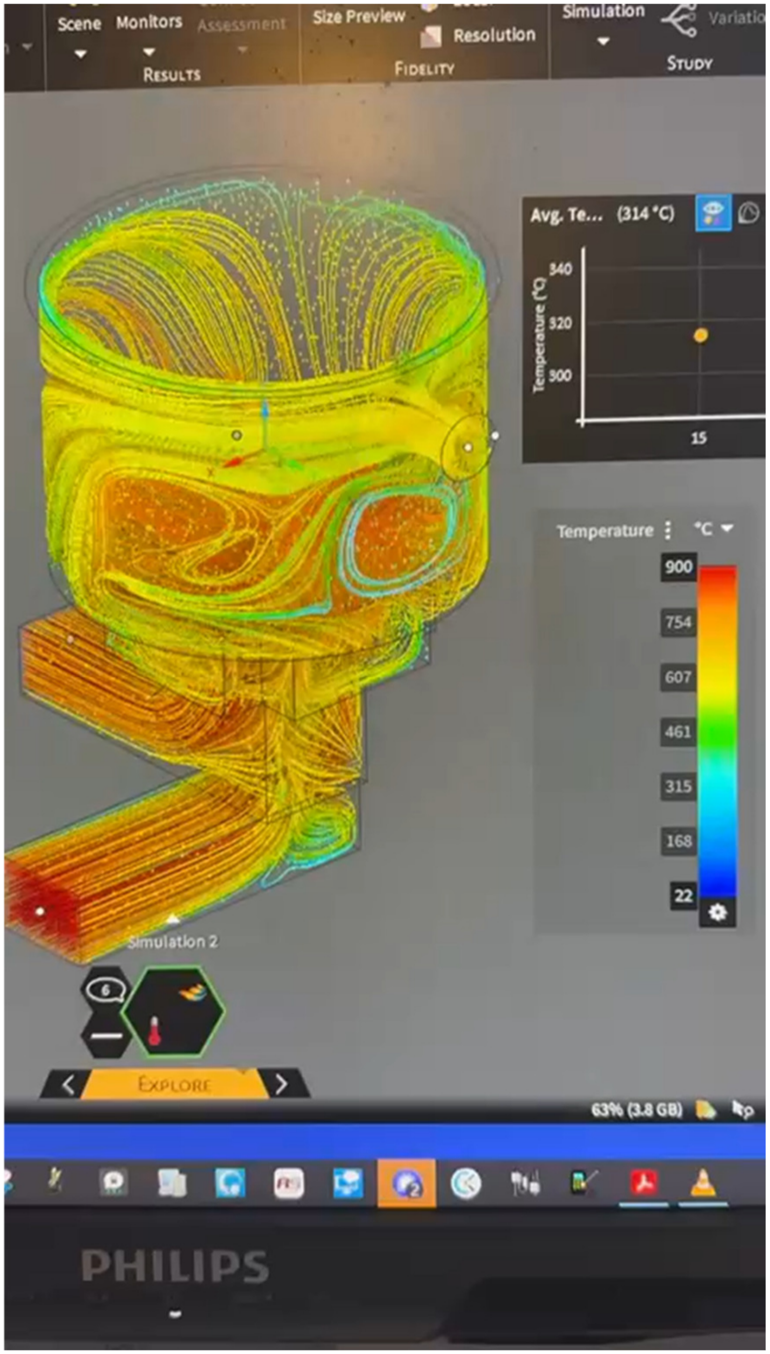


Clove oil distillation in rural Madagascar

Now the vanes have been added, copying the same height ratios as were used in the KB 4.1.

The vanes dramatically changed the flow pattern, driving hot gases around the pot to the front and across the top.

The modelled exit temperature dropped from 462° C to 314° C. The heat gained by the pot increased by 20% for this simple addition at a cost of about $30.

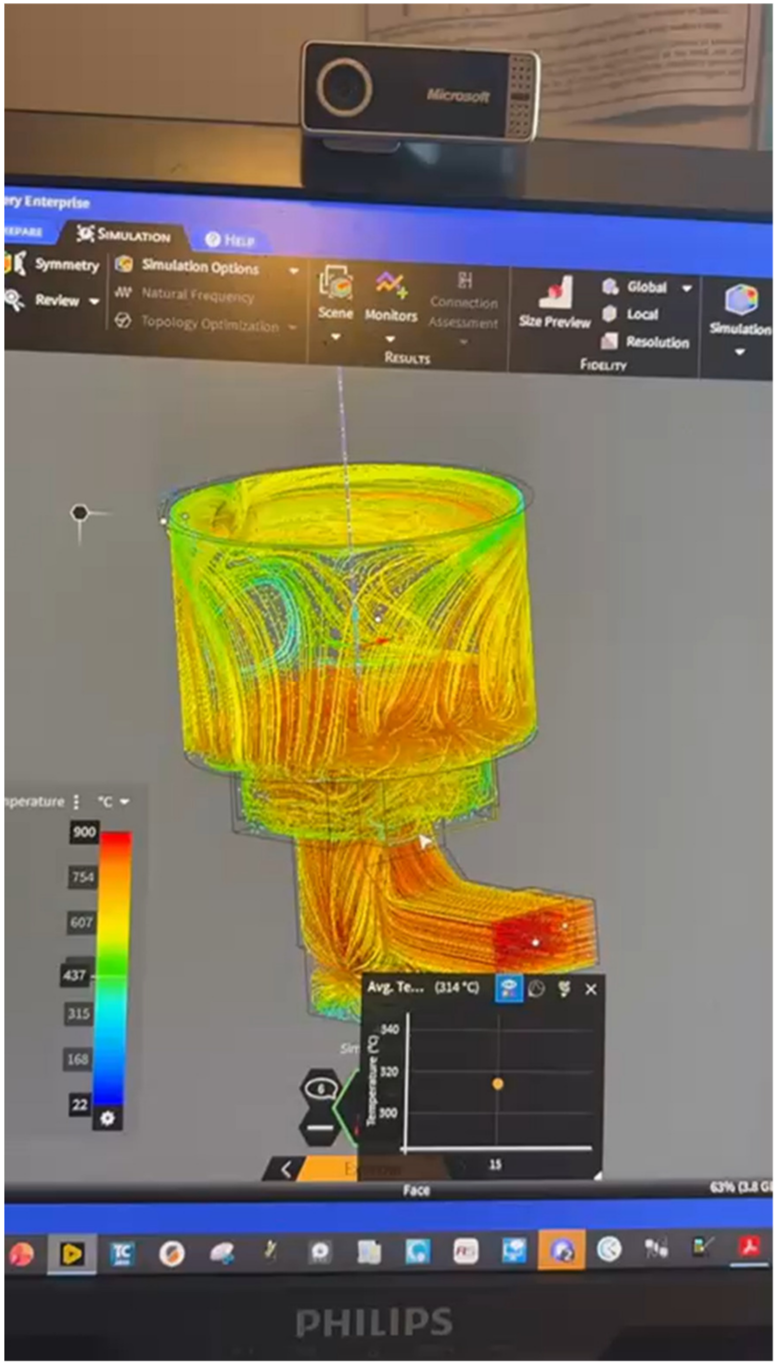


Clove oil distillation in rural Madagascar

This video shows that the model can be rotated while it is running. A detailed examination of each section can be made.

Additionally, the dimensions of the physical model can be altered using the drawing functions, and the simulation will re-balance within a few seconds.

It is this capability that allows the developer to test dozens of iterations per hour without requiring access to a high-performance computer.

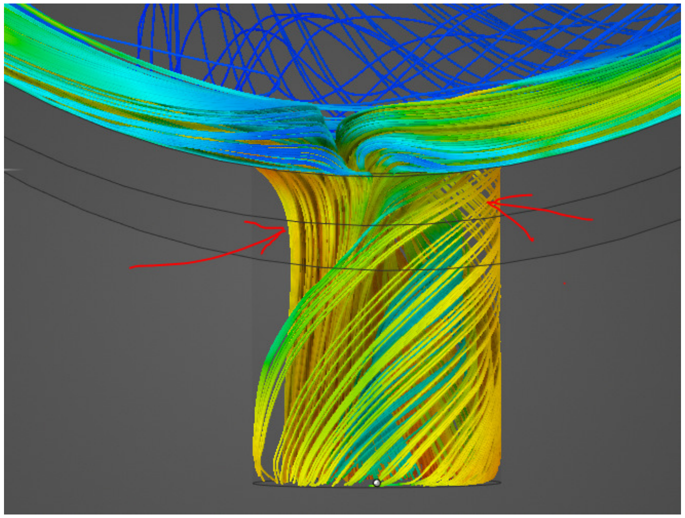


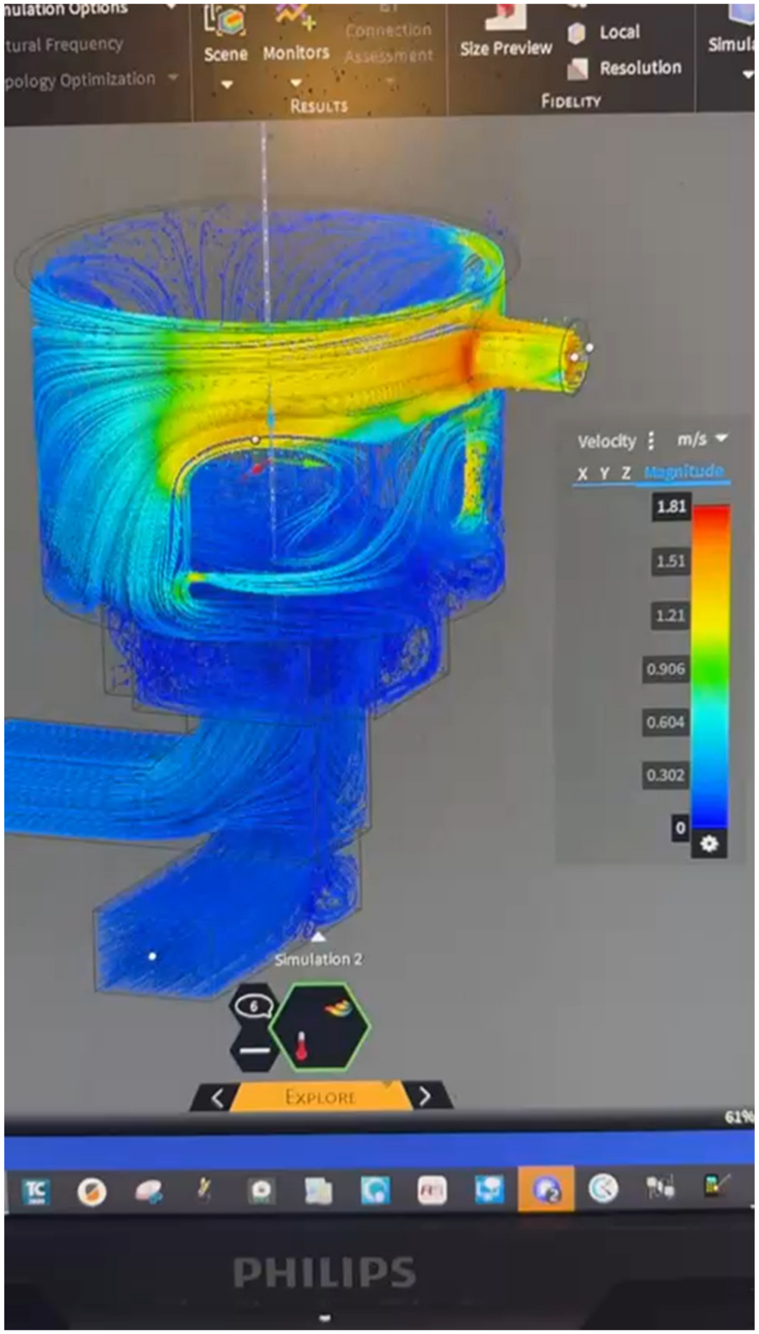
Clove oil distillation in rural Madagascar

This is a Velicity map of the gas flow.

Note that that the highest velocity is at the entrance of the tube leading to the chimney. This is a sharp-cornered entrance which indicates that it should be radiused at perhaps 1/3 of the tube diameter.

With a sharp corner, the velocity is approximately 50% higher than the velocity in the tube. This is an unnecessary restriction and easily corrected.





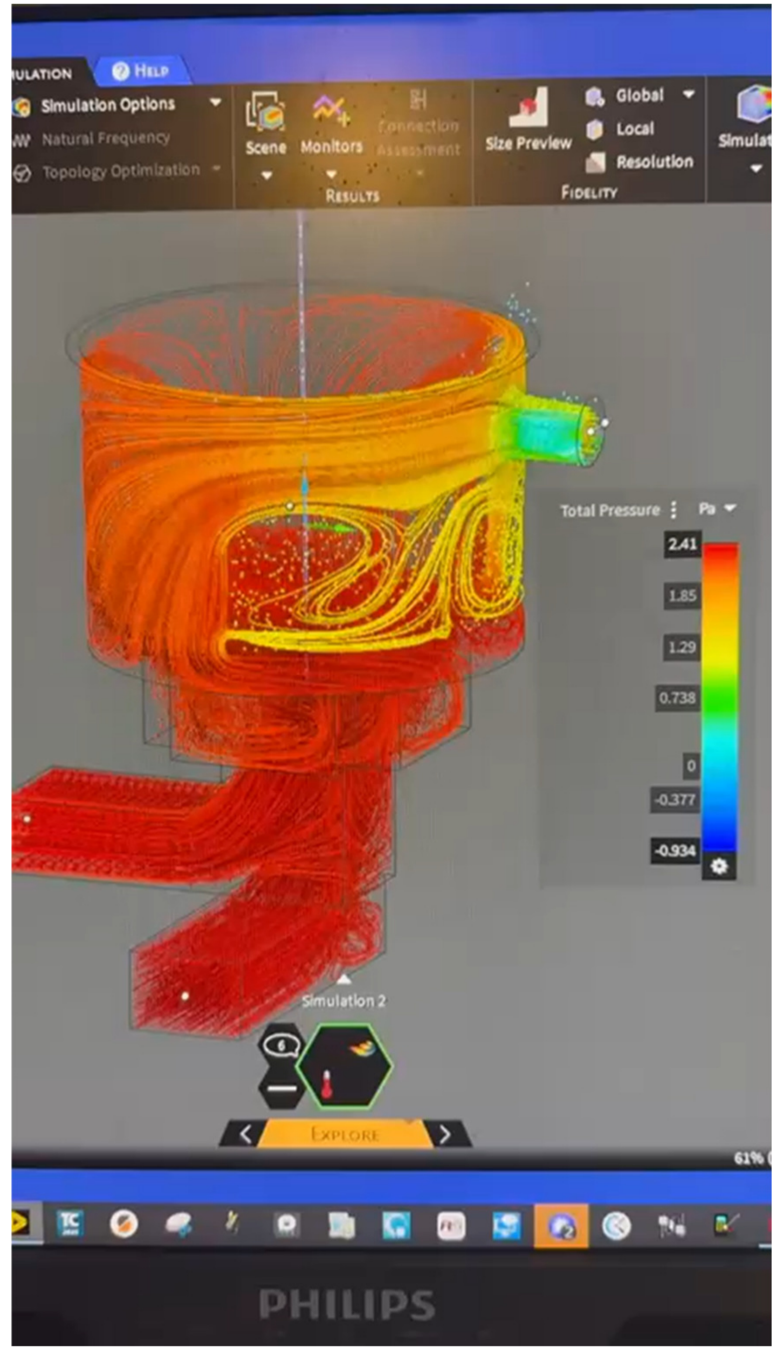
Clove oil distillation in rural Madagascar

This shows the same view with the flowlines representing pressure.

What to look for here is that the pressure in the chimney is the lowest in the whole simulation. If there is a higher pressure in that tube, there definitely will be smoke emerging from somewhere.

The zone at the back of the pot, bounded on 4 sides by vanes, is pulling gases through 4 ports the size of which have been determined by experimentation, using the “Pull” function of the program. Clearances can be adjusted to see the effect in real time.

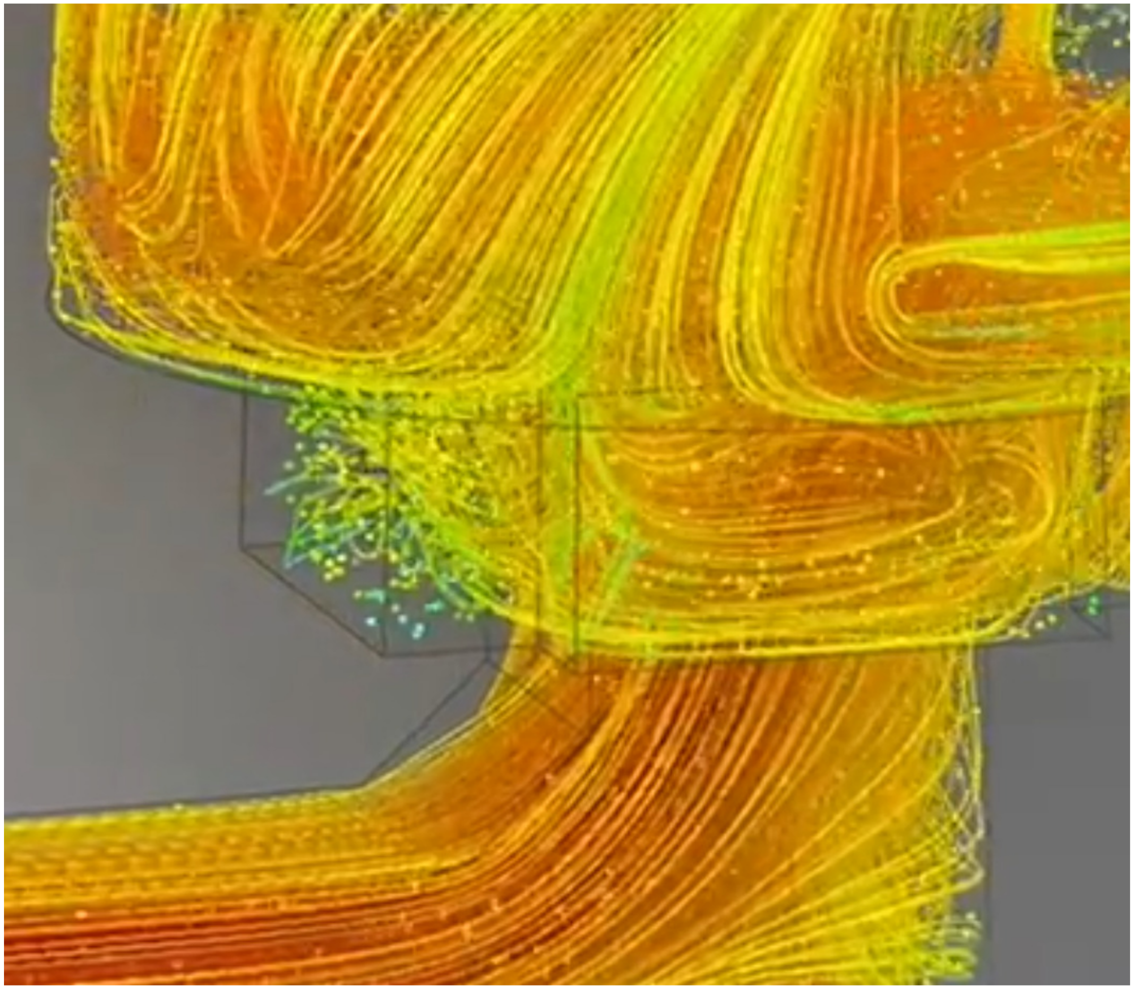
This simulation is using 3 million cells which is adequate for testing ideas.



END

Thank you for this opportunity to demonstrate what modern science and engineering can bring to simple biomass burning devices that are the backbone of rural farming and employment.

The materials used for these structures include common bricks, cement, stainless steel sheets and a small quantity of refractory materials.



The KB 4.x cooking stove for schools saves 45% of the fuel compared with “improved stoves” and 70% compared with traditional structures.

Our expectation is that the clove oil distiller will save at least 33%-50% of the fuel. It is presently under construction.

Thank you!

Appreciations:

Our host: the Beijing Academy of Agriculture and Forestry Sciences

Our organizer: Institute of Data sciences and Agricultural Economics, which organized the 2025 *International Symposium on High-Quality Development of Artificial Intelligence and Agricultural Engineering Consulting Conference*

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