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Review IJETA

Mathematical Modeling and CFD Analysis for Protype Model Development of a Low-cost Hybrid Power Operated Mini Kitchen Chimney for Rural Households

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Abstract

Home chimneys remove pollution by products of fossil fuels from the atmosphere. Today's environmental problems are worsening rapidly due to technology and population growth. Thus, researchers developed a hybrid micro kitchen chimney to help rural residents at a low cost. This small hybrid chimney simplifies rural cooking. A kitchen chimney is the best way to remove smoke, grease, stink, stains, oil droplets, and more from the kitchen. It helps ventilate the kitchen. Choosing the best option is difficult. This study introduces a hybrid mini-kitchen chimney for rural areas to improve performance, reduce household air pollution, and save energy. Our present work uses CFD to estimate and assess the flow mechanics in and around the kitchen chimney region. CFD study results will inform kitchen plan refinement. Sunlight powers the hybrid chimney.

Keywords: hybrid mini kitchen chimney, rural areas, CFD, Solar power, optimum performance.

INTRODUCTION

Cooking is essential, so the kitchen is important. Vapours from cooking must be removed from the kitchen. Chimney hoods keep kitchens clean and healthy. Biomass is the main cooking fuel for over three billion people. Gas cooking requires combustion, which requires oxygen. To meet combustion and ventilation needs, a high ventilation rate is needed, which increases energy consumption. Clean air and pollutant removal are critical for exhaust hood performance. Solid cooking fuel is the main source of household air pollution (HAP) in rural India. Firewood, cow dung, wood, agricultural leftovers, and other solid fuels are most common. HAP causes two-thirds of the national disease burden and is one of the world's worst issues. 68% of Indians live rurally. Solid fuels heat 90.2% of this rural population, while mixed fuels heat the rest. Many governments, NGOs, and academic organisations have developed answers to this issue. Improved cook stoves (ICs) are a popular and fast way to reduce HAP emissions. The most basic "improved cook stove" is a three-stone chimney-equipped stove. Smoke chimneys come in numerous varieties. Some chimneys have built-in fans and mechatronics, but they need electricity to work. The cost of these chimneys is high, and when electricity is not present, they are not in working condition and fill the room with smoke. Sometimes, it is also not affordable, so here is a concept for a natural conventional hood type chimney without power supply to remove the most smoke from the kitchen [1-5].

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LITERATURE REVIEW

It compares present and prior efforts. The current implementations that solve the project's issues and limits are shown, and the future development is focused on. It should be straightforward. Kitchen ventilation hood research is summarised. A good kitchen hood ensures a healthy, comfortable, and energy-efficient working environment. The ideal kitchen ventilation design accounts for appliance heat gain. "Correction and analysis of calculation equations of the thermal plume above kitchen appliances" by Zhao et al. in "Procedia Engineering" examines convection plume calculation equations. Cooking equipment features a Gaussian temperature and velocity distribution from a point heat source. At the extraction point, the kitchen's transitional zone's convection flow is not fully developed. Thus, our generic plume equation fails in the twilight zone. In real-world applications, user- modified virtual origin locations yield reasonable precision. In [Zhao et al. (2017)] [16], air flow rate virtual origin formulas are created. "Correlations of control parameters determining pressure distributions in a vertical exhaust shaft," published in Building and Environment, found that high-rise buildings' local exhaust hoods' ventilation performance affects the exhaust shaft's pressure distribution. Due to insufficient hood fan exhaust airflows and considerable infiltration, gap gaps from unequal pressure allow unwanted noise to enter. The height of the building, shaft size, roof fan features, hood fan use, and outside air temperature affect pressure distribution in a vertical shaft. This study sought to understand the vertical shaft's ventilation performance and measure and examine the effects of each parameter using numerical methods. For this, dedicated simulation software was created. This programmed applied fluid dynamics to vertical air columns with horizontal branches. Simulating a 25-story apartment building yielded the results. Variance was examined to determine if parameters were related. The results demonstrated a substantial correlation between the pressure distribution deviation based on a modest negative value (30 Pa or 40 Pa) and the shaft's greatest pressure. Thus, using pressure deviation as a single objective parameter produced an insufficient and unbalanced pressure distribution across the shaft. Pressure control in the vertical shaft may also use roof fan speed, inlet damper opening, and sensor parameters such pressure and pressure gradient at the topmost level and outside temperature. "Experimental and computational investigation of indoor air quality inside several community kitchens in a large campus," published in Building and Environment, examined air quality in kitchens on the campus of a large Indian institute. Kitchen air quality was investigated. Four campus kitchens were cautiously chosen after a thorough preliminary inspection of their cooking setups and exhaust systems. An indoor air quality monitoring system called IAQ Calc7545 was utilised to detect temperature, CO2 and CO concentrations for the experiment. Each kitchen had a 1.8-by-1.5-metre vertical space. This area is perpendicular to the vertical side of a hob facing the cooks, and measurements were obtained at 72 grid points that were regarded acceptable. Fluent simulates the three-dimensional fluid flow field in the kitchen at site 1 for computational reasons. A separate FORTRAN algorithm for equilibrium chemical analysis calculates CO2 and CO volume fractions. These estimations become fluent simulation boundary conditions. Burner exit calculations are made. The mixture model for multiphase flow is the most accurate for calculating species distribution in Fluent's flow domain. CFD modelling matches tests despite the geometry and flow field's complexity. This verifies boundary conditions, grid generation, and other details. [Saha et al. (2012)][17] compares measured and computed values to ASHRAE standards.

One of the biggest challenges influencing indoor air quality and health is particulate matter from cooking. Cooking particles' properties, especially size distribution, must be known to estimate an individual's exposure. "Volume-based size distribution of accumulation and coarse particles (PMO. 1-10) from cooking fume during oil heating" was published in "Building and Environment" and characterised the fume particles at the oil heating stage for typical Chinese-style cooking in a laboratory kitchen. We need a laser-diffraction size analyzer to measure fume particle volume frequency from 0.1 to 10 millimetres. These particles make up most of PM2.5 and PM10. The measurements show that particle emissions are closely related to heating temperature and relatively independent of vegetable oil type. Mode, median, Sauter, and De Broukere mean diameters are 2.7, 2.6, 3.0, and 3.2 mm, respectively. Distribution is 0.48 millimetres. 100% of PM0.1e10 is fume particles between 1.0 and 4.0 millimetres. This study [Gao et al. (2018)] [18] collected emission characteristics to improve indoor air quality assessments caused by PM0.1e10 in the kitchen and residential flat.

Based on a survey of existing scientific literature, the research gaps that follow are being identified.

- Until now there has been few research done on the hybrid mini chimney.
- There is no research on low-cost chimneys and also no research that focuses on rural area people issue with household pollution which can affect their health in long term.
- The idea of hybrid mini chimney is introduced by us in this project.

There are very limited research works available elsewhere mainly focused on optimal parameters of kitchen hood for commercial kitchens that highlights Indian commercial scenarios[6].

MATERIALS & METHODS

Kitchen size, chimney material, and chimney proportions all influence the shape of the chimney hood cover. To collect the most smoke from the hob, the end closest to it is usually angled outward. The opposing end, which serves just to direct smoke and other pollutants beyond the kitchen, is typically a straight portion. The geometry of the hood cover for a typical mid-sized home's chimney was taken into account for this investigation [7]. The hood rises a total of 0.408 metres above the ground. The top section is curved as the chimney is made for rural area; so that it can fit in the window side. The angle X° here is decided on the basis of CFD analysis so that mass flow rate of steam should be maximum through the chimney. The bottom part of chimney has a dimension of 450mm x250 mm, this consideration is made for mid-size kitchen. In Figure 1 below the dimensions of the chimney are shown. The chimney consists of hood with draft angle of 40 degrees and the hood dimensions are 450mm x 250 mm with the exhaust pipe dimension of 105mm x 105 mm.

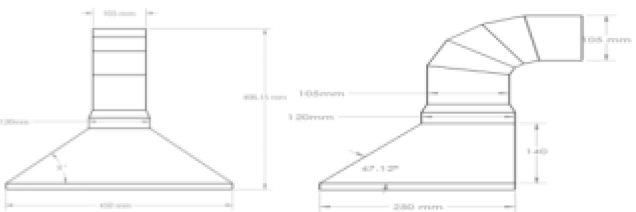

Figure 1. Specifications on the geometry of the kitchen vent hood cover.

In the below Figure 2 the Inlet and outlet of the mini chimney shown. The inlet is the part through which the air is suck by the chimney and the outlet is the part at which the toxic sucked are thrown out of the room [8-10].

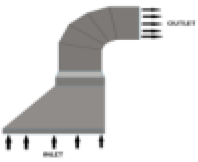

Figure 2. Cover for a kitchen chimney modelled as a boundary for CFD analysis.

The following Figures namely 3, 4, 5 and 6 are the different views of our proposed mini chimney model developed in Solid works software (2016) environment which are available in our department. The views contain front view, side view, top view and bottom view of the mini chimney model (Figure 7,8).

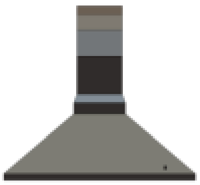

Figure 3. Front View of mini chimney

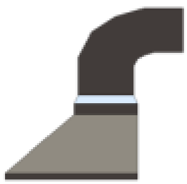

Figure 4. Side View of mini chimney.

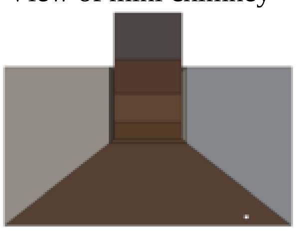

Figure 5. Top View of mini chimney

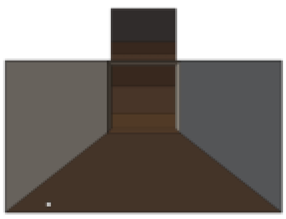

Figure 6. Bottom View of mini chimney.

Figure 7. Assembly of Chimney.

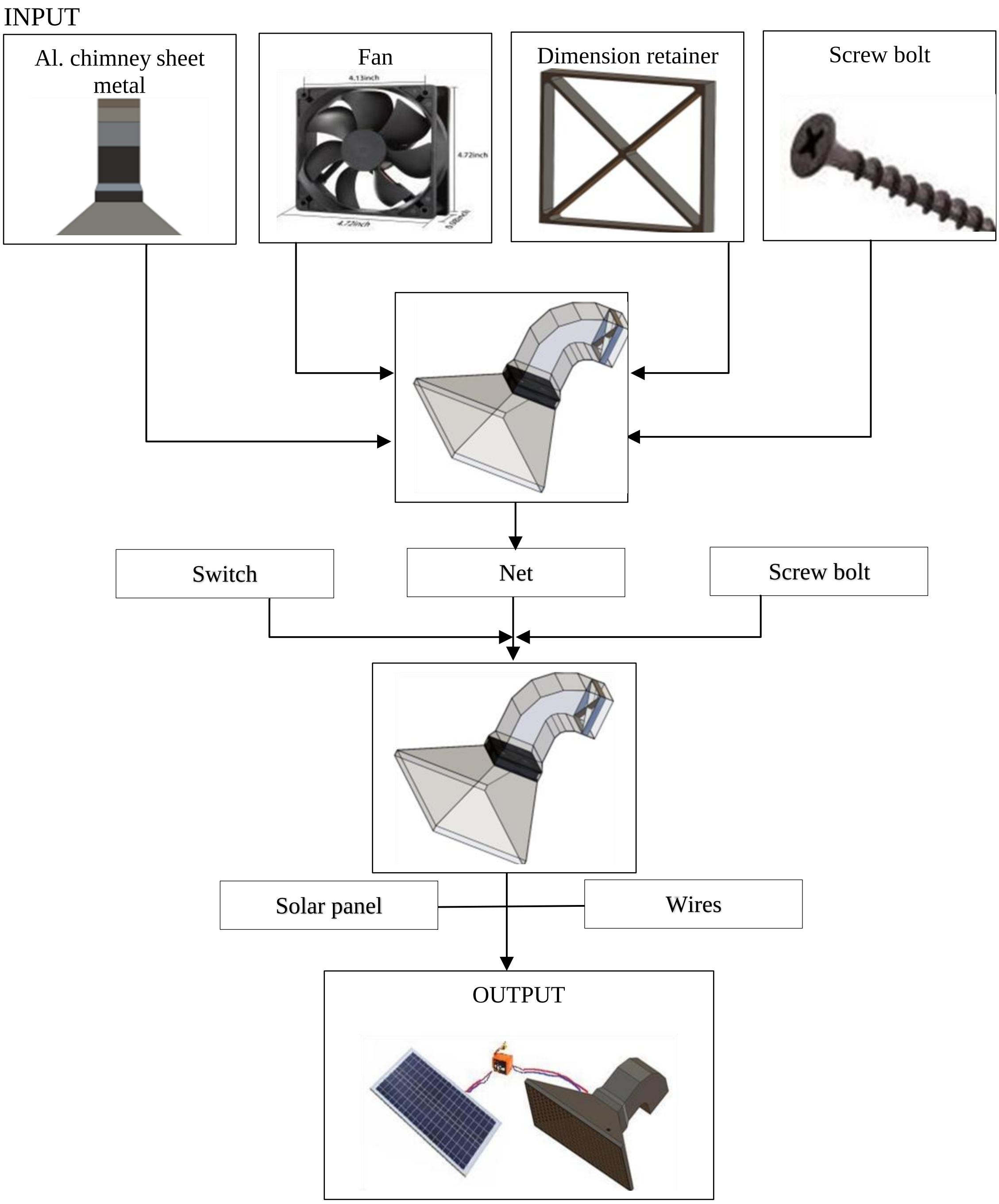

Figure 8. Assembly block diagram.

MATHEMATICAL MODELING & CFD ANALYSIS

Solver Details

Four models of a kitchen hood chimney have been made using the SOLIDWORKS 2016 programme. A constant 450mm x 250mm is used for the size of the hood's base. Chimney configurations include (a) a flat or 0-degree setup (b) a 35-degree Draught angle setup (c) a 40- degree Draught angle setup (d) a 45-degree Draught angle setup (e) a 60-degree Draught angle setup. ANSYS 19.2 is used for the CFD analysis [11-13].

MESHING DETAILS

Ansys 19.2 was used to model and mesh the CFD domain. The kitchen chimney hood is the realm that has been modelled. The boundary layer mixing phenomenon has been taken into account throughout the meshing process. Due to boundary layer mixing, the mesh close to the wall must be adjusted to capture the tiniest flow data. As a result, the captured flow physics is more accurate and the derived findings are more precise. Since the flow is unimpeded and continuous in the zone closer to the core flow, a coarser mesh is used to designate this area. Because of the added resistance from the wall, the flow closer to the wall will take a fraction of a second longer to reach the outlet. Since fine mesh is defined close to the wall portions, computation time increases in such circumstances. Different iterations are performed while keeping an eye on the meshing size, and the meshing size is set at the point where the results converge [14-16].

RESULT

The simulations were run to determine the best draught angle for the kitchen chimney hood to minimize pressure drop. In this study, we looked at the effects of a wide variety of draught angles, from 0 degrees to 60 degrees. Since pressure loss is greatest in this situation due to stagnant flow, hood covers with a zero-degree (flat) draught angle are often not advised (Figure 9,10)

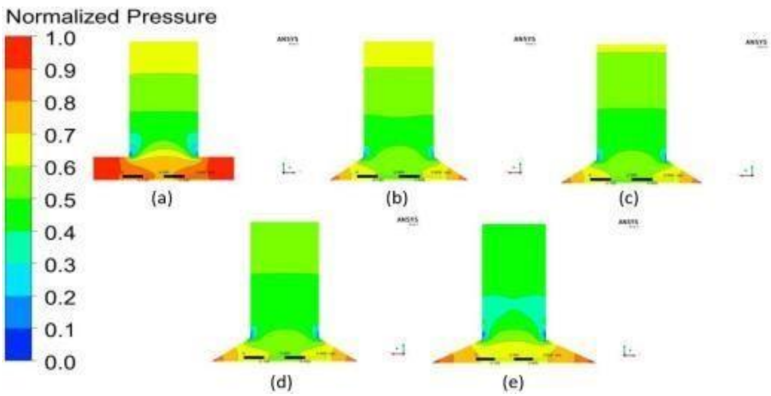

Figure 9. Pressure contours (a) flat (b) zero-degree 35°,40°, 45° and 60° Draught angle

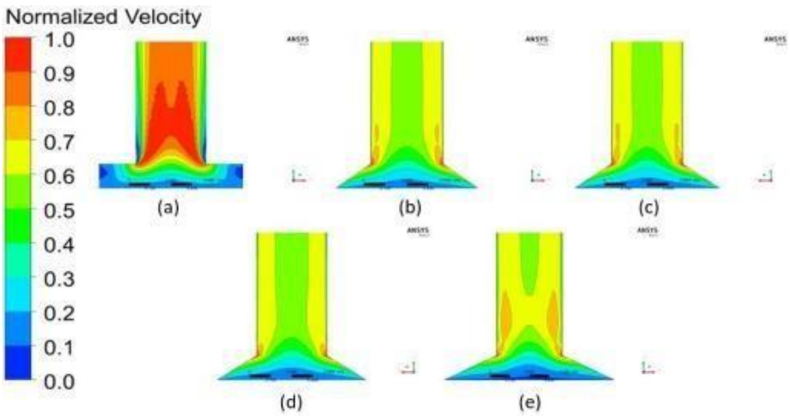

Figure 10. Velocity contours (a) flat or zero-degree (b) 35°, 40°, 45°and 60° Draught angle

In Figure 11,12,13 According to the analysis we choose the angle of 40 ^{0} degree and the CFD analysis of that shown in Table 1,2

Table 1. Properties of steam.

Steam Properties Density	1.17989 kg/m3
Thermal Conductivity	0.02603 W/m-K
Dynamic Viscosity	1.85505e-5 Pa-s
Specific Heat	1003.62 kJ/kg K

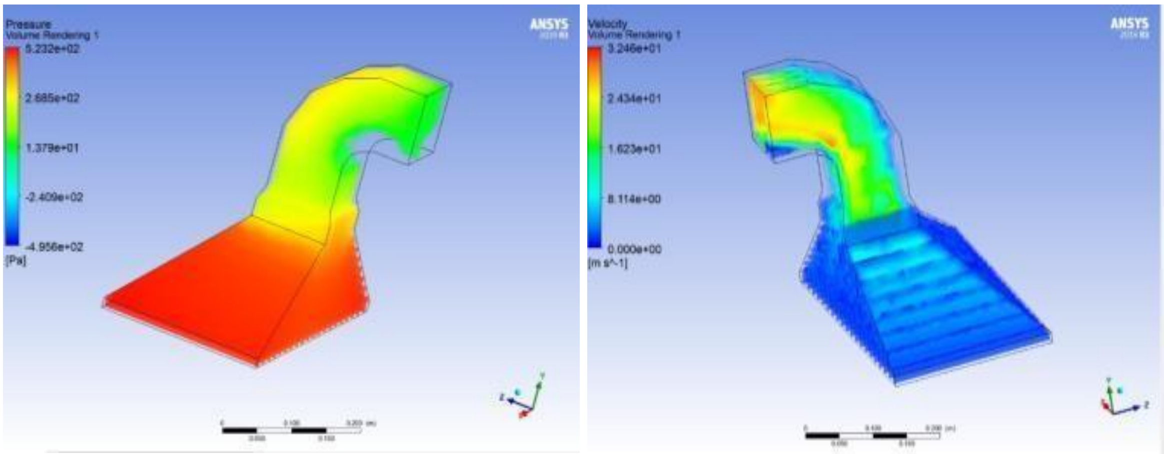

Figure 11. Pressure and Velocity contours for draft angle of 40º of chimney.

Table-2: CFD analysis result

Configurations 11	**Mass flow rate, kg/min**	
	CFD	*Experimental*
Flat Walls	2.2836	-
35º	1.9425	-
40º	2.8005	-
Max. Stress	107.8 Mpa	
Max. Deformation	0.17 mm	

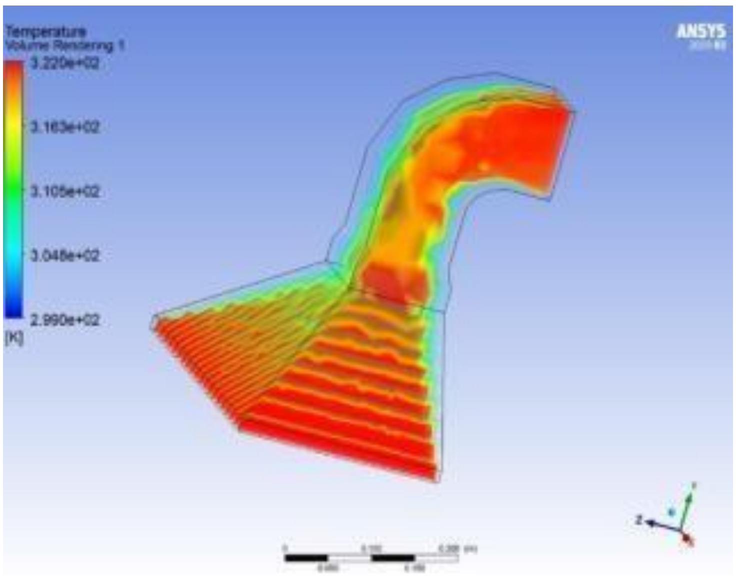

Figure 12. Temperature contours for draft angle of 40º of chimney.

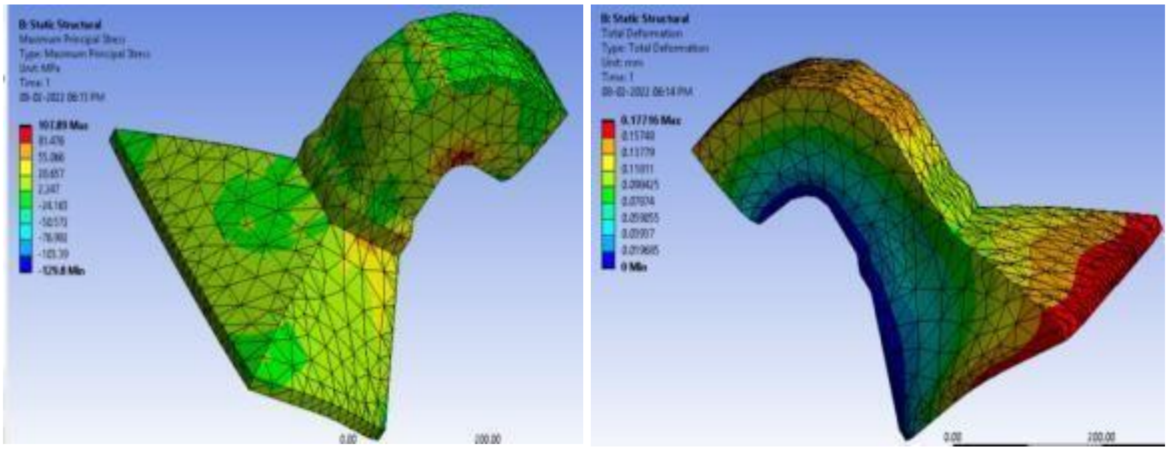

Figure 13. Stress and deformation due to temperature variation

GRID INDEPENDENCY TEST

An investigation into grid independence is carried out with the goal of removing or lessening the impact that the number of grids and the size of the grids have on the outcomes of the computation. In addition, it is best practise to adhere to this for every unique piece of geometry, which can be very tiresome. The grid independence test for certain geometry will only be relevant for that particular geometry (Figure 14).

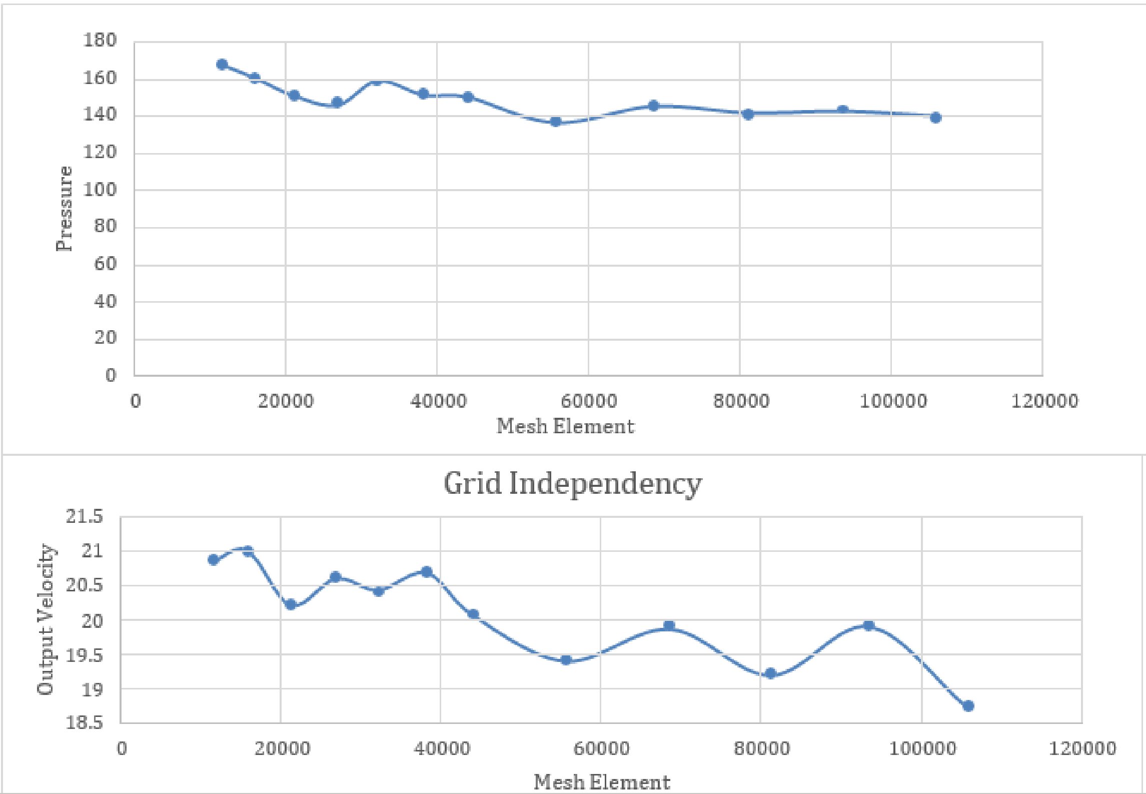

Figure 14. Grid Independency Test.

According to this, Grid Independency test properly perfect meshing size should be identified from our mesh model and then conversing should be expected but above our 2-grid independency curve trend in between 15000 to 40000 followed by nodes of 3560 to 8900 to be converged but due to improper meshing and less time at this moment expected converge portion found not yet up to the level of satisfaction what was expected.

DISCUSSIONS

Compare the performance of different chimney wall designs through CFD modelling and experimental testing. The chimney's efficiency will be measured by its capacity for high mass flow, or the rate at which a given amount of fluid may be expelled under standard conditions. The velocity at the chimney's outflow was used to determine the mass flow rate. An anemometer was used to measure the wind speed at the chimney's opening. Mass flow rate was estimated using the average velocity.

DESIGN OPTIMIZATION

Chimney size decision: Over a period research regarding the size of the chimney has been done. The size parameters which are taken into consideration are the hoods width and breadth. The width (W) and the breadth (B) are shown in Figure 15 below.

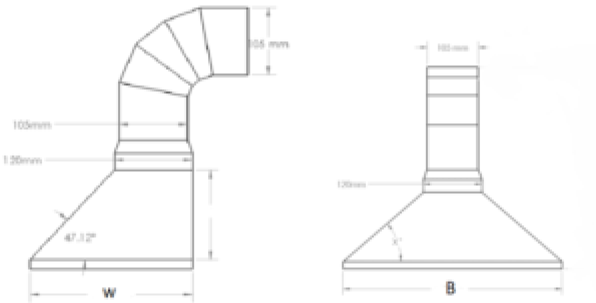

Figure15. W & B Considerate Image.

Following are the some projects of chimney with their dimensions and source are given in figure 16,17,18-

Figure 16. Research Chimney 1, Mini Chimney W=25 cm and B=35 cm

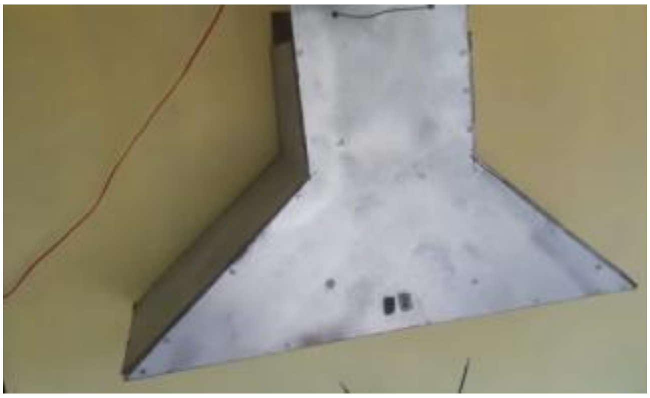

Figure 17. Research Chimney Mini chimney W=30 cm and B=50 cm

Figure 18. Research Chimney 3, Mini chimney W= 26 cm and B=38 cm.

With the help of this research, we have considered the design dimension as shown in the below 19 image. And the angle of the hood got from the CFD analysis.

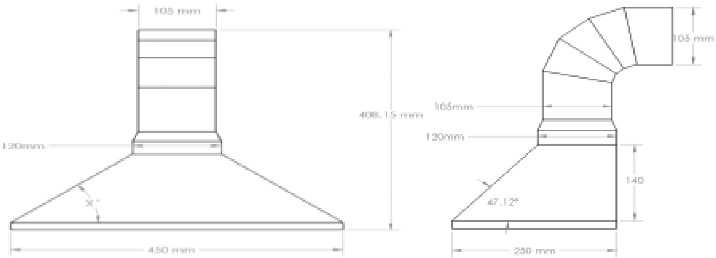

Figure 19. Final optimized design dimensions.

WORKING LAYOUT MODEL FOR HYBRID MINI-CHIMNEY

There are several hybrid sources that can be used to power a mini chimney, including solar, wind, and biomass energy. These sources can be combined to create a more sustainable and efficient system. For example, a mini chimney could use solar panels to generate electricity during the day, wind turbines to generate electricity during windy conditions, and biomass fuel to generate heat when the other sources are not available. By using a hybrid system, the mini chimney can operate more efficiently and reduce its environmental impact. However, the specific design of the hybrid system would depend on factors such as location, climate, and available resources.

The main layout for the project prototype is based on solar energy, where solar panels are used to generate electricity which is stored in a battery. The energy from the battery is then supplied to a mini chimney, enabling it to operate using renewable energy sources, resulting in a sustainable and eco-friendly system(Figure 20).

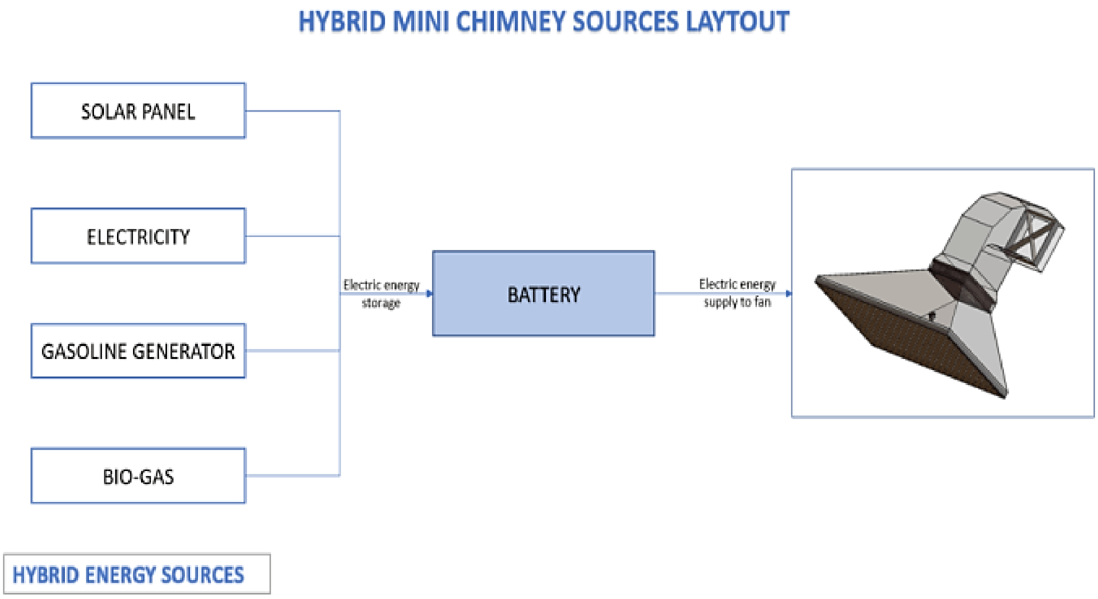

Figure 20. Hybrid Mini Chimney Layout.

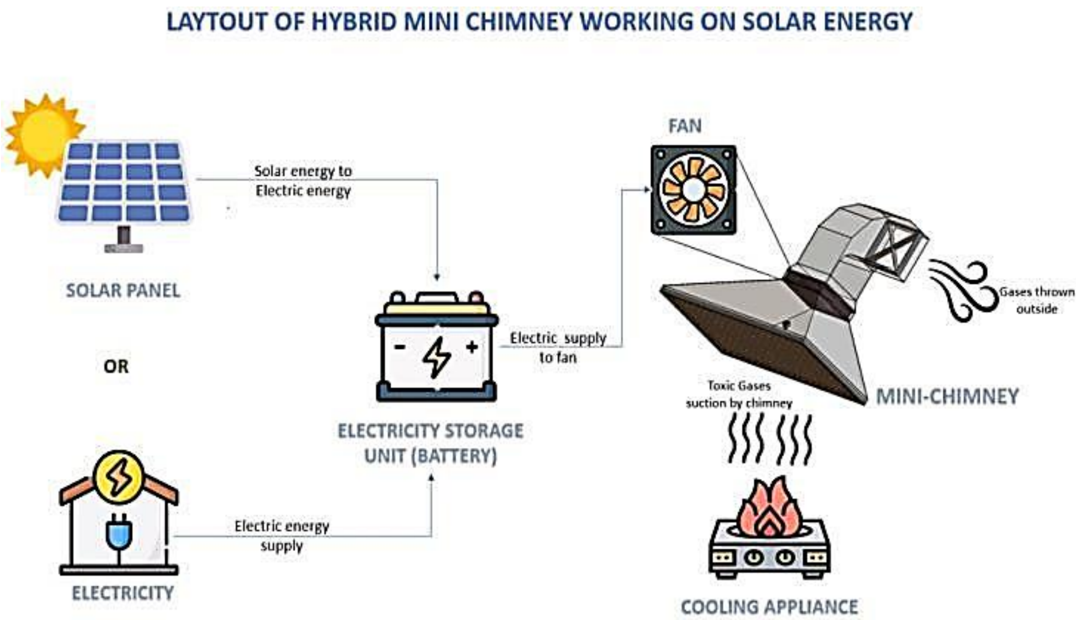

Figure 21. Hybrid Mini Chimney Laytout on Solar Energy

The main layout for the project prototype is based on solar energy, where solar panels are used to generate electricity which is stored in a battery. The energy from the battery is then supplied to a mini chimney, enabling it to operate using renewable energy sources, resulting in a sustainable and eco-friendly system (Figure 21).

Other Sources that we have taken consideration to supply power to mini chimney are discussed briefly below Figure 22:

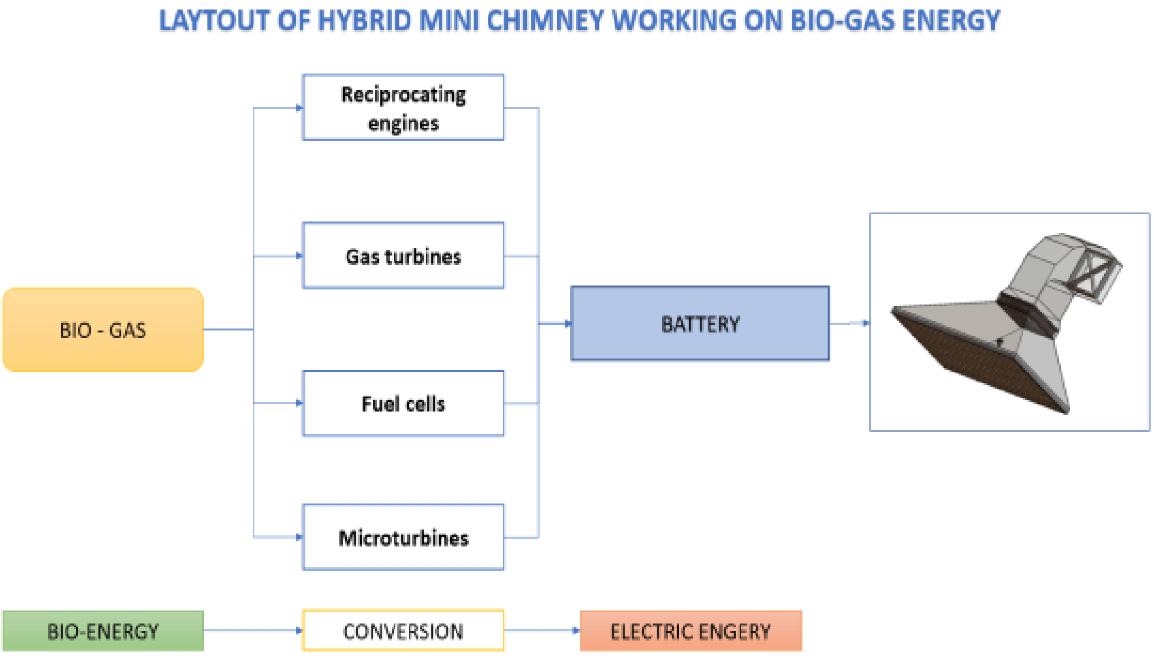

Figure 22. BIO-gas to electric energy.

Here are some common techniques:

1. *Reciprocating engines:* This method involves using an internal combustion engine to convert biogas into electricity. The engine is fueled by biogas, and as the gas is burned, it drives a generator to produce electricity. Reciprocating engines are widely used in biogas power plants, and they are efficient and reliable.
2. *Gas turbines:* Gas turbines work similarly to reciprocating engines, but they use a different combustion process to generate electricity. Biogas is burned in a combustor, and the resulting hot gas is used to spin a turbine that drives a generator.
3. *Fuel cells:* Fuel cells are an alternative to traditional combustion-based methods of generating electricity. In this method, biogas is processed in a fuel cell to produce electricity directly. Fuel cells are highly efficient and produce very low emissions, but they can be expensive to install.
4. *Micro-turbines:* Micro-turbines are small, compact turbines that can be used in small-scale biogas systems. They work similarly to gas turbines, but they are smaller and more efficient. Microturbines can be used to generate electricity in remote areas or for backup power.

Here are a few examples:

1. *Gasoline generators:* Gasoline generators are similar to internal combustion engines, but they are specifically designed to generate electricity. They use petrol to power an engine, which in turn drives a generator to produce electricity. Gasoline generators are widely used in backup power applications, but they can be noisy and emit pollutants(Figure 23).
2. *Micro-turbines:* Micro-turbines are small-scale combustion turbines that can be powered by petrol. They are highly efficient and produce low emissions, making them a good option for distributed power generation. However, microturbines can be expensive and require regular maintenance.
3. *Fuel cells:* Fuel cells can be powered by hydrogen, which can be generated from petrol using a reformer. Fuel cells convert the chemical energy in petrol directly into electricity, with high efficiency and minimal emissions. However, fuel cells can be expensive and require a constant supply of fuel.
4. *Stirling engines:* Stirling engines can also be powered by petrol. They use heat to expand and contract a gas, which drives a piston to generate mechanical energy. Stirling engines are highly efficient and can run on a variety of fuels, but they are relatively expensive and not widely used.

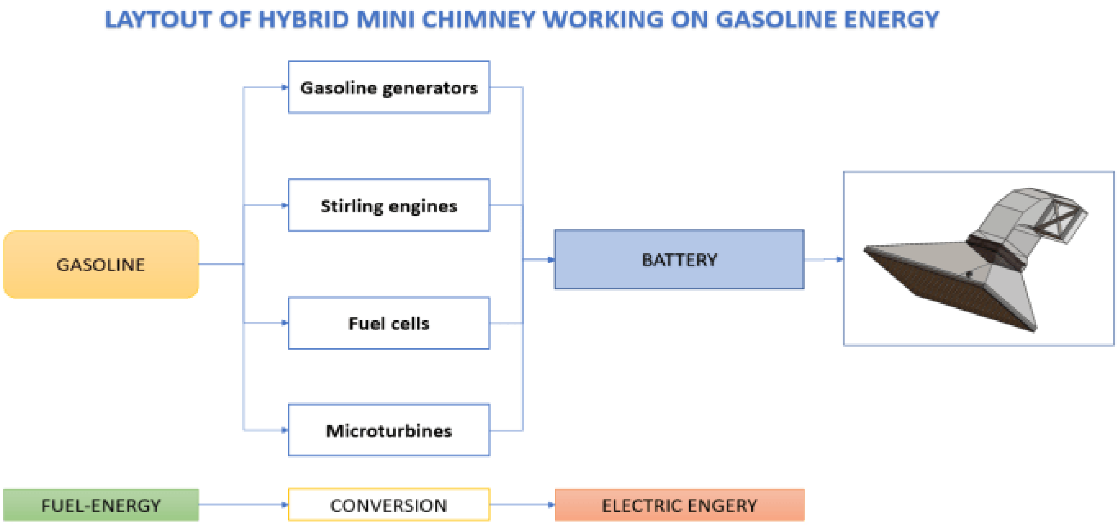

Figure 23. Gasoline to electric energy.

COST ANALYSIS

As we know that our hybrid mini chimney is made for rural areas. Thus, we must perform the cost analysis where we'll try to reduce the cost of our chimney as much as possible because our chimney should be economically affordable and well as properly working up to the mark. Thus, cost analysis becomes an essential task to perform for our hybrid mini chimney. The components Hybrid Mini Chimney are:

Fan

The motor is having rated power of 3w capacity with max 2000 rpm per min, their specifications are as follows:
Rated voltage – dc 12 v Watt- 3 watts
Current – 0.15 A

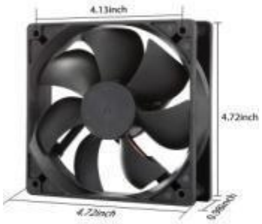
Figure 24. Fan

The cost of a 12V dc motor of 3W with rotor fan comes in the range - Rs 149 (Figure 24)

Sheet Metal Frame

The cost of Aluminium sheet metal AISI 304 used in the preparation of chimney is: Rs 249 (Figure 25)

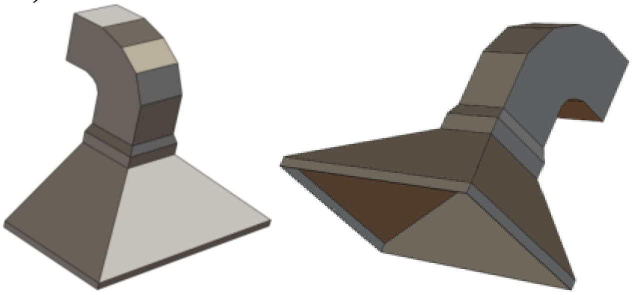

Figure 25. Chimney.

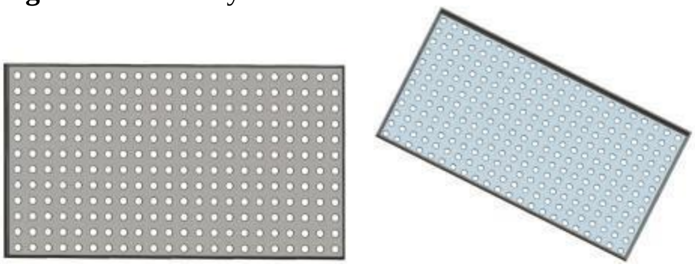

Figure 26. NET.

Figure 27. Retainer

On off switch

The cost of a good quality on-off switch: Rs 20 (Figure 28)

Figure 28. Switch

Solar panel

The cost of a solar panel: Rs 990 (Figure 29)

Figure 29. Solar plate.

This implies that the total cost required for the preparation of our hybrid mini chimney will be around Rs 2500-2600. Thus, we can see that our chimney is economically affordable; culturally viable and naturally suitable. Also, when we look at our chimney it's does not take a lot of effort and cost in installing it our kitchen (Figure 26,27).Table 3, 4 show the material of bill

Table3. Bill of material.

Item	Part Name	Purchased	Fabricated	Vendor	Qty	Material Cost	Labour Cost	Extended Total
1	Chimney hood		**X**		1	448	50	498
2	Battery Pack (12V)	**X**			1	750	0.00	750
3	Solar panel (12V)	**X**		Ece India pvtlmt.	1	990	0.00	990
4	On/Off Switch	**X**		IndiaMart	1	20.00	0.00	20
5	Exhaust Fan (12V)	**X**		PANO-MOUNTS	1	149	0.00	149

6	Electric Wire	**X**		IndiaMart	1	30	0.00	30
7	Diode	**X**		IndiaMart	4	2	0.00	8
							TOTAL	2445

Table 4: Material Details for the chimney hood

Part Name	Material	Density	Unit	Weight	Rs/Unit	Cost (Rs)
Al Sheet metal	AISI 304 Sheet metal	0.01	1	1.72 kgs	249 (Rs/kg)	423.12
Rivet	Stainless steel	7.93		-	2	24
					Subtotal:	448

Labour Cost for manufacturing

The manufacturing process for the mini chimney involves cutting, bending, and riveting sheet metal parts. The cost per chimney unit includes material costs, labour costs for cutting, bending, and riveting, as well as overhead costs such as rent, utilities, and insurance. The total cost per unit is the sum of all these costs. The cost related to this per chimney unit are given below the Table 5

Table 5. Labour Cost for manufacturing.

Manufacturing Process	Rs/Unit	Cost (Rs)
Cutting	10	10
Bending	7	7
Riveting	8	8
Subtotal:		25

Labour Cost for Assembly

Assembling the mini chimney involves fitting the fan inside the chimney, wiring the fan to the on-off switch, and attaching the switch to the chimney. The cost per unit includes labour costs for assembly, cost of electrical components such as wires, switches, and connectors, as well as overhead costs such as rent, utilities, and insurance. The total cost per unit is the sum of all these costs. The cost related to assembly given below Table 6

Table 6. Labour Cost for Assembly

Assembly Process	Rs/Unit	Cost (Rs)
Fan fitting	10	10
Wiring	7	7
On/off switch fitting	8	8
Subtotal:		25

CONCLUSIONS

Based on the observation of the study the following conclusions are made carefully:

- The effect of different draft angle for domestic chimney hood type chimney is presented.
- It can be determined that adjusting the angle has a substantial impact on the performance of the chimney.
- The chimney with a draught angle of 40° produces the optimum results.
- In the current investigation, total base area was held constant while the effects of draught angle modification were studied.
- For the hybrid chimney solar power is used as nowadays in rural area this facility is acquired by people.
- The partial cost analysis is done, and our hybrid mini chimney model at this moment found very low cost however in actual there may be certain increase of cost which will be more effective and cheaper for all level of rural household.

- Further our proposed model expected to be safer for all rural households' people of inhaling kitchen smoke and protect from many health issues.

Future scope

- Use of a fibre material instead of aluminium sheet metal can be done so that weight is reduced, and the mass manufacturing is more efficient.
- Additional features can be added like bulb in a chimney so that it can provide light on the hybrid mode as we are using solar panel.
- Can also convert the hot steam energy into any other energy source.
- We have designed our project and that has been known by us that there will so many ample numbers of future scope to be carried out in the next phase of our major project-2to bring a real level of hybrid mini chimney model for successful use of rural household peoples.

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Data Availability

The authors confirm that this study's data are in this research report.

Conflict of Interests

All the authors contributed equally and have no conflict of interest in any way with this paper.

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