Development of a Flame Shield for use in Domestic Gas Stoves

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Abstract. Gas stove is one of the most common and basic domestic appliances found in any home in the subcontinent. It is the foremost article used for cooking at home, and thus necessitates interaction with it by the users in a significant way. Despite the advent of more advanced devices like the microwave oven or the induction cooktop, a traditional gas stove reigns supreme in the lives of homemakers. Therefore, an endeavor was undertaken to design a product that would improve the usage and performance of a gas stove, by way of alleviating the general problems faced by users in its operation. Design thinking strategies had been followed throughout the stages of the product development, beginning with a customer survey to understand the desirable needs, followed by translating them into tangible target specifications for the product to achieve, and finally using the ideation techniques to develop the concepts into feasible product. The morphological method of concept generation yielded possible concepts aimed towards a solution, which were evaluated by following the analysis techniques of Forced Decision (FD) and Decision Alternative Ratio Evaluation (DARE). The filtered concept was then subjected to product architecture design, where it was given an efficient physical form by using the Computer Aided Design (CAD) software SolidWorks, and lastly, the parametric design result was evaluated by means of various Design For Excellence (DFX) guidelines. The product turned out to be an appendage to the existing stove, that would shield the flame and provide efficient operation along with enhanced safety and ease of use, as validated by DFX principles and a Computational Fluid Dynamics (CFD) study to gauge its performance in relation to that of a standalone gas stove. This paper comprises of expositions of all the aforementioned processes as carried out, along with the final result, and pertinent analyses.

1. Introduction

A stove is a device that burns fuel or uses electricity to produce heat inside or on top of the apparatus [1]. Essentially, the device has become a common kitchen appliance of late, where it is used to generate warmth for cooking meals. These stoves are powered by gas predominantly, and used in kitchens everywhere, from restaurants to homes. The first resemblances to stove can be found in the Middle Ages, where hearths made of brick and mortar, which were as high as a person’s waist, came into being. Around 1728, cast iron ovens started becoming prevalent. These primordial ovens known as Five-plate or Jamb stoves originated in Germany. The French architect, Francois de Cuvillies provided a design
for the oldest proper gas stove with an enclosure, in 1735. The Benjamin Franklin’s all-metal fireplace was invented in 1743 and following that Rumford stove around 1800. Philo Stewart designed and patented the first compact wood-burning cast-iron stove called the ‘Oberlin’, in 1834, which went on to become a huge commercial success [2]. In India, the use of LPG primarily for running gas stoves has soared from 0.405x109 kg in 1980–1981 to 8.157x109 kg in 2002–2003 and it has been predicted to increase further, up to 9.66x109 kg in 2010–2011 and 12.63x109 kg in 2015–2016 [3]. An increase of this measure – especially if it happens in other developing countries as well - will further diminish the already scarce fossil fuel reserves of the world [4]. For the case of India, it has been predicted that 96.6x106 kg of gas could be conserved, based on the gas usage in 2010-11 of 9.66x109 kg, by effecting just a meagre 1% increase in the efficiency of operation of the stove. This would conserve a considerable amount of money, along with conservation of fossil fuels. In the past few years, numerous studies can be found aimed at improving the efficiency of cook top burners, which is dictated by heat transfer properties, and the combustion performances, which are in turn determined by the design parameters of burner, stove and pot.

The literature survey conducted at the commencement of our project has revealed that there have been quite a number of research work carried out, aimed at providing a new, improved version of the common gas stove, but however, the approach that we decided to try out was more inclined towards designing a novel product that would grant the optimized performance results to an existing gas stove, perhaps acting like an appendage to it, so that the product need not compete with established gas stove players, but could create a niche area for itself. The product was envisioned to incorporate the effects of efficient performance, as well as comprising features that would prove to be solutions for a few common problems faced in kitchens while cooking. To this, new product development principles had been made use of, which covers the complete process of designing and introducing an avant-garde product to the market. The problem statements had been received from a sample size of users, which were then translated to the target specifications correspond to the requirement a product has to fulfill. Then followed the stages of conceptualization, concept evaluation, concept refinement, computer-aided design, validation and characterization. The results of this project have been documented carefully and exhaustively in this paper.

2. Research Methodology
The rest of the paper elucidates the process of designing a product catering to customer needs. The following sections begin by translating the results of a customer survey conducted electronically to be made use of, for product development.

2.1. Concept Formulation
An initial customer survey was conducted in order to frame the problem statements to be eliminated. It included questions pertaining to the responder’s time spent in a kitchen on average, in addition to the problems and suggestions for improving the usage of stove in a kitchen. This was done in order to make sure that the results were based on the opinions of people who really knew what they expressed [5].

2.1.1. Product’s target specifications. The needs have been drafted from the survey in such a way as to provide the best chance of minimizing or obviating the problem considering tangible and feasible product design. [6]. Table 1 shows a list of the most significant problems that were expressed by the majority of the customers at the end of the survey.

| S. No. | Customer Statement                        | Interpreted Need                                                        |
|-------|-------------------------------------------|------------------------------------------------------------------------|
| 1     | Stove needs to facilitate ventilation     | Channelling heat from source towards vessel and away from user          |
|       | measures                                  |                                                                        |
2. Stove must not come in the way of being able to use fan/AC
3. Controlling Heat Radiation
4. Insulating hot apparatus
5. Safety warning system

Channelling heat from source towards vessel and away from user
Channelling heat from source towards vessel and away from user
Channelling heat from source towards vessel and away from user
Indication when stove is on and burning

2.1.2. Concept Generation by Morphological Method. Morphological analysis is a well-developed procedure used in industry for new product concept generation. It employs the concept of systematically tackling a multi-dimensional solution to a problem through the relationships between its associated nuances. It is based on bringing together two opposing notions: decomposition and forced associations [6]. Morphological method helps in giving a glimpse into potential alternative combinations that could be considered. In Table 2, all possible solutions that there could be to the problem have been vaguely identified and included with the motivation to leave no stone unturned, which have been described in terms of parameters that would shape the outcome, which can be considered as distinct functions of the variable “x”, with each possibility (numbered from 1 to 4) of a parameter being considered as possible values that the variable could take up in the function; or in other words, the domain of the function [7]

| Parameter | Possibility - 1 | Possibility - 2 | Possibility - 3 | Possibility - 4 |
|-----------|-----------------|-----------------|-----------------|-----------------|
| Shape     | Cylindrical     | Cuboidal        | Trapezoid       | Frustum         |
| Structure | Constant        | Variable        | Variable length and breadth | Combination of all |
| Nature of variability | Variable diameter | Variable length and breadth | Expandable (Telescopic mechanism) | Retractable |
| Mechanism for variability | Foldable | Expandable (Iris mechanism) | Expandable (Telescopic mechanism) | Retractable |
| Area Coverage | Entire stove | Individual Burner | >1 Burners | Capable of doing both |
| Mode of operation | Manual | Automatic (Electronic) | Automatic (Hydraulic) | - |
| Height | Beneath burner | Beneath vessel | In line with burner | Beyond burner and vessel |
| Roof | Top open | Top-closed, load-bearing | Top closed, slender | Retractable roof |
| Relation to vessel | In contact | Not in contact | Load-bearing | - |
| Location | Enclosing vessel | Between vessel and burner and drip tray | Between vessel and cooktop | Between vessel and cooktop |
| Distance from Burner | Resting on burner | Resting on drip tray | Resting on cooktop | Supplanting the drip tray |
| Coverage to Burner | Covering burner alone | Covering burner and entire vessel | Covering burner and vessel partially | Covering burner and vessel and entire vessel |
| Heat Indication | Temperature sensor activated alarm | Real time temperature display | Thermochromic material (Visual color change) | - |
2.1.3. Filtration of concepts. At the end of formulating the morphological chart, and before generating the concept combination table, an intermediary process was followed in order to scrutinize the concepts superficially and eliminate any explicitly unfeasible or detrimental value of “x” or possibility. This was done so that the concept combination process would be focused on those concepts which carried more promise. Out of the 14 aforementioned parameters, eight parameters had been selected and assigned one specific value of “x”, which was feasible. The rationales put forth in the attribution of one choice to a parameter have been mentioned in Table 3.

| Parameter                | Choice          | Reasoning                                                                 |
|--------------------------|-----------------|---------------------------------------------------------------------------|
| Structure                | Variable        | An adjustable equipment is preferred due to the need to account for various sizes of vessels |
| Mechanism for variability| Expandable by iris mechanism | Iris mechanism is the most effective among the potential alternatives to be deployed |
| Area Coverage            | Individual Burner | It is better to have each burner compartmentalized, because of the large differences in stove dimensions and to save space |
| Mode of operation        | Manual          | To make the model lighter and simpler, it can be made to be operated by hand, since it is not strenuous to do so |
| Height                   | In line with burner | Picking a pliable iris mechanism would do away with the need for adjustments in height |
| Relation to vessel       | In contact      | Having the device in contact with the vessel would give rise heat conduction, but it is essential for establishing effective heat containment. The trade-off is achieved by picking a suitably heat resistant material for manufacture |
| Location                 | Between vessel and cooktop | This is the ideal region for placing the device, so that it does not need to be constructed larger than or smaller than what is required |
| Coverage to Burner       | Covering burner alone | This would suffice to ensure maximum coverage of flame |

2.1.4. Concept Combination Table. This is a tool that helps to concatenate fragments of solutions and yield combinations of those to be systematically scrutinized. The columns in the Table 4 correspond to the parameters, were determined to show promise in all their original considered variable values. The entries in each column are said values, which had been picked out to form meaningful combinations with other values of the remaining parameters that would function well together.

| Concept | Shape     | Nature of Variability | Roof                        | Distance from Burner | Heat Indication              | Material       |
|---------|-----------|----------------------|-----------------------------|----------------------|-----------------------------|----------------|
| 1       | Frustum   | Variable diameter    | Top closed, Load bearing    | Resting on drip tray  | Real time temperature display| Polymer        |
| 2       | Cylindrical | Variable diameter  | Top open                    | Supplanting the drip tray | Thermochromic material      | Stainless steel |
2.2. Concept Selection
The best concept is the best possible outcome at the end of the concept formulation process, and would be taken through the subsequent process of embodiment design. To determine that, the weightages were computed against the each requirements specified by the users using Forced Decision and DARE analysis as mentioned below:

2.2.1. Forced Decision (FD). The reduced number of concepts are needed to be evaluated against the weightages or importance given by the customers during the survey on specific attributes expected to have in the product that to be designed. Forced Decision (FD) analysis, used to methodically recognize, analyze and adjudge the priorities of the requirements to have [8]. Table 5 shows the functional descriptions, which are essentially the specific descriptors based on which the concepts generated will be put to test in later stages [6]. Each combination of descriptions has been subjected to a head-to-head shootout at the end of which one winner was determined and these results had been tallied to provide the rank attributed to all descriptions, denoting their standing.

Table 5. FD Analysis.

| Functional Description                      | Comparative Evaluation | Total | Rank |
|---------------------------------------------|------------------------|-------|------|
| A Portability and compactness               | A: 0 B: 0 C: 0 D: 0 E: 1 | 1     | 5    |
| B Ease of cleaning                          | A: 0 B: 0 C: 0 D: 0 E: 0 | 0     | 6    |
| C Effectiveness of heat radiation containment| A: 0 B: 0 C: 0 D: 1 | 1     | 5    |
| D Safety warning effectiveness              | A: 1 B: 0 C: 0 D: 0 | 0     | 1    |
| E Versatility of use                        | A: 1 B: 0 C: 0 D: 1 | 1     | 2    |
| F Ease of use                               | A: 1 B: 0 C: 0 D: 0 | 0     | 2    |

2.2.2. Decision Alternative Ratio Evaluation (DARE) Analysis. After prioritizing the functional descriptions, DARE analysis was applied on by what degree each factor exerted superiority over the others. This information was vital to attribute weights to each factor for the final stage of concept selection [9]. The DARE analysis illustrated in Table 6 has been done to calculate the degree of importance of one descriptor when compared with the adjacent descriptor. According to the ranks developed by the FD analysis, the attributes have been arranged.

Table 6. DARE Analysis.

| Functional Description                      | J | K     | W     | Functional Description |
|---------------------------------------------|---|-------|-------|------------------------|
| 1 Effectiveness of heat radiation containment| 1.3| 1.3   | 2.67696 | 25.6                  |
2.2.3. Concept Scoring. Concept scoring is used to establish a qualitative hierarchy of design options. The relative importance of each criterion has been gauged and it helps towards more accurate comparisons among concepts, as shown in Table 7. This makes use of the 5 outcomes arrived at, by the end of concept combination, and rates them on the basis of the factors obtained at the end of FD and DARE analyses and the importance attributed to each of them. Of the concepts in question, the Concept - 2 has been found to carry the most desirability on the basis of a weighted score attributed to each concept by virtue of their rating on a scale of 1-5 achieved towards each attribute, and the criticality associated with that particular attribute, among the others [10].

|         | Attributes                        | (%) | 1  | 2  | 3  | 4  | 5  |
|---------|----------------------------------|-----|----|----|----|----|----|
|         | Effectiveness of heat radiation containment | 25.6 | 4  | 1.024 | 4 | 1.024 | 2 | 0.512 | 4 | 1.024 | 3 | 0.768 |
|         | Safety warning effectiveness     | 17.9 | 3  | 0.537 | 4 | 0.716 | 5 | 0.895 | 4 | 0.716 | 4 | 0.716 |
|         | Versatility of use               | 19.7 | 5  | 0.985 | 5 | 0.985 | 2 | 0.394 | 3 | 0.591 | 4 | 0.788 |
|         | Portability and compactness      | 12.3 | 2  | 0.246 | 5 | 0.615 | 4 | 0.492 | 3 | 0.369 | 3 | 0.369 |
|         | Ease of use                      | 14.9 | 3  | 0.447 | 4 | 0.596 | 3 | 0.447 | 2 | 0.298 | 3 | 0.447 |
|         | Ease of cleaning                 | 9.6  | 4  | 0.384 | 3 | 0.288 | 2 | 0.192 | 3 | 0.288 | 3 | 0.288 |
| Total   | Score                            | 3.623 | 4.224 | 2.932 | 3.286 | 3.376 |
| Rank    |                                  | 2    | 1  | 5  | 4  | 3  |

2.3. Embodiment Design.
Embodiment design entails determining the final design layout, encompassing arrangement and compatibility of interactions, the product geometry and dimensions (including materials), the plan for production, and solutions for any rectifications needed in anywhere in between [11].

2.3.1. Product architecture. It is a plan for arranging the fundamental functional elements employed in the device, by allocated spaces of their own, and for laying down how they have to interact [12]. Figure 1 shows a schematic diagram of our product’s architecture. The different parts required to carry out the desired functions are represented by white boxes. The pink boxes represent individual parts that perform a function on their own. The bigger green boxes containing a few white-boxed and pink-
boxed entities represent “chunks”, which are agglomeration of parts to perform a common function. The interactions between entities are depicted by orange lines denoting unification as one physical structure and blue lines denoting transmission of forces.

![Figure 1. Schematic view of Product Architecture.](image)

Based on the schematic diagram, which shows how the parts of the product are to be arranged in space, geometric layout is established as shown in Figure 2, based on which the fundamental and incidental interactions could be identified later on [13]. The different representative individual entities described earlier have been condensed as proper components in this layout.

![Figure 2. Geometric layout.](image)

2.3.2. **Configuration Design.** The design of the product needs to take into account the space available for the design of each part on the product, so that the interactions identified earlier could continue as envisioned [14]. A detailed description of the product parts and its dimensions are given in Table 8. The design was made such that it could be placed on a typical Indian gas stove.

| S. No. | Part     | Description                                                                 | Dimension Range (mm) | Reasoning                                                                 |
|--------|----------|------------------------------------------------------------------------------|-----------------------|--------------------------------------------------------------------------|
| 1      | Enclosure| Circumference split into individual entities called “fins” with grooves for attaching linkages | Diameter: 80-250 | All possible sizes of vessels to be accommodated and contact with burner to be avoided. |
2 Linkage Each fin is attached to its own linkage that works like a connecting rod. Length: 70-75 Should not protrude out of base diameter

3 Mechanism A slotted-lever mechanism where the circular provision featuring the slots rests on the base and the linkages are driven by said lever. Helps to maintain uniform motion among all fins. Slot width: 6-10 Thickness: 4-6 Lever diameter: 6-8 Lever height: 12-15 Entire setup has to be within the confines of the base and slim enough to not buckle

4 Base Circular provision housing the slots for lever, and keeping the fundamental structure intact. Diameter: 80-100 Thickness: 8-10 Size of largest possible burner or smallest possible vessel

5 Handle Essentially, more of a lever that is contiguous with the lever in the slotted-lever mechanism, and also operates the same. Height: 15-20 Thickness: 8-12 Large enough to be gripped and pulled by human hand, without adding too much weight

2.3.3. Parametric design. The selected concept had been defined holistically using all possible theoretical parameters, before beginning the parametric design phase using SolidWorks CAD software. There were five different parts that had to be built and assembled together to form the actual product. The model obtained at the end of the designing phase has been illustrated below, with a visual of the entire assembly in Figure 3, followed by the bill of materials in Table 9.

![Flame Shield-Isometric View](image)

**Figure 3.** Flame Shield-Isometric View.

| Item No. | Part name        | Quantity |
|----------|------------------|----------|
| 1        | Link             | 16       |
| 2        | Fins             | 16       |
| 3        | Pins             | 48       |
| 4        | Plastic handle   | 2        |
| 5        | Pin handle       | 6        |

**Table 9. Bill of Materials.**

3. Computational Fluid Dynamics Study of the Flame Shield
The final chosen design had been validated using Computational Fluid Dynamics (CFD) to understand if the new commodity really did bestow an improvement in operation to a stove, over how it is being
used presently. To gauge this, the parameters chosen are temperature within the region enclosed by flame shield, wind velocity in the same space, and pollutant emission from the burning of fuel in the stove. The analysis performed using ANSYS has been described in detail in the section that follows. This CFD simulation is validated by comparing the contours and results obtained in this paper to a published previous numerical investigation of cooking gas stove burner [15]. A similar concept has been extended to the domain of our application and the flame shield model is added to perform further investigation.

3.1. Geometry and Meshing
A conventional burner is modelled using SolidWorks with an inner diameter of 30 mm, and outer diameter of 80 mm, respectively, where the burner is 15 mm high. The number of holes on the inner and outer sides is same, and is 30 in the upper row, and 60 in the bottom row.

The flame shield model is imported into the domain and an enclosure is made around the shield to create the fluid domain. In order to avoid complexity, only the fins of the flame shield are considered in the CFD simulation. The handles, pins, and links are disregarded as they do not contribute much to the aerodynamic and thermal characteristics. Meshing is performed using the standard tool available in ANSYS. Body of influence is used to get more refined mesh near burner region.

3.2. Fuel Properties and Boundary Conditions
The parameters of the fuel and oxidizer are provided along with the inlet and outlet condition variables and their values in Table 10. The boundary conditions applied on the domain are illustrated in Figure 4. The simulation has been designed to consist of an environment where a ceiling fan is running near to the stove during operation [16].

| Fuel Name | Mass Fraction Value |
|-----------|---------------------|
| C3H8      | 0.7546              |
| C4H10     | 0.2453              |

| Oxidiser Name | Mass Fraction Value |
|---------------|---------------------|
| N2            | 0.7206              |
| O2            | 0.1834              |
| H2O           | 0.0959              |

| Mixture Properties | Value |
|--------------------|-------|
| Thermal Conductivity (W/mK) | 0.0138031 |
| Dynamic Viscosity (g/cm-s) | 7.4504×10⁻⁵ |

| Inlet Boundary Condition (Unit) | Value |
|---------------------------------|-------|
| Mass of air (kg/hr)             | 2.33  |
| Mass of fuel (kg/hr)            | 0.15  |
| Velocity of air (m/s)           | 1.17  |

| Outlet Boundary Condition (Unit) | Value |
|----------------------------------|-------|
| Pressure (Pa)                    | 0     |
| Temperature (K)                  | 273   |

![Diagram of simulation setup](image)
3.3. Turbulence Model
Reynolds-averaged Navier–Stokes model which is the k-epsilon model available in ANSYS Fluent is used for calculating the turbulent characteristics. Non-premixed combustion model is chosen which is the best fit for household gas stove burners combustion. The mixture fractions and other parameters are entered to get the PDF graph which is then implemented for combustion calculations.

3.4. Results and Discussion
The values of velocity distribution, temperature contour, and NOx mass fraction (pollutant) are evaluated by the results of the CFD simulation done using conventional setup of burner and burner equipped with flame shield, which also helps to model the nature of flow phenomena and quality of performance. Two cases are simulated with and without the wind phenomena and comparison between the cases, as well as difference on the results with and without flame shield is shown.
3.4.1. Temperature. The temperature contours have been studied when an airspeed of 1.17 m/s is implemented on both regular and flame shield burners, at their midplane. This particular wind speed is typical area average airspeed from a ceiling or table fan. The temperature distribution is shown in Figures 5 and 8. There is a vast difference in the maximum temperature of standard and flame shield burners. The maximum temperature for standard and flame shields is 1230K and 1880K respectively. Thus, it is evident that the flame shield protects the flame and restrains the incoming high-speed wind. Also, in the conventional case, the presence of wind narrows down the flame expansion which leads to uneven cooking. The flame shield prevents the wind thus maintaining the distribution of flame and temperature thus providing better and faster cooking.

3.4.2. Velocity. The velocity contours are shown in Figures 6 and 9. The airspeed around the vicinity of the burner is 1.65 m/s and in the case of flame shield, it is just around 0.566 m/s. Thus, the fins are preventing the impacts of high-speed air. This is also the reason why the temperature is high in the case of the flame shield.

3.4.3. Pollutant. Thermal NOx comprises a majority of NOx produced when gases and light oils are combusted. Generally, the rate of NOx production is substantially high when the temperature of the flame exceeds 1800K. Thus, for this simulation where the combustion of LPG is taking place, only the thermal NOx is calculated. Thermal NOx is shown in Figures 7 and 10. The maximum mass fraction of NOx in the case of the flame shield is $4.75 \times 10^{-08}$ and for the conventional burner is in $10^{-12}$ which is negligible. The high pollutant for the flame shield is due to high temperature. As mentioned before when the temperature exceeds 1800K the NOx reaction increases rapidly. Thus, there is a trade-off between the temperature and pollutant. High temperature is required for faster and efficient cooking but at the same time pollutant also increases.

4. Conclusion
This paper essentially explains the processes involved in formulating a new product, right from the inception, to the validation of the designed product, with a walkthrough along the stages of conceptualization, visualization and product design, substantiated with documentation of the results obtained at the end of each decision-making procedure, with the evaluation rationale provided, even with calculations in relevant parts. All these comprise the design and development of a “Flame Shield” - a device to act as a supplementary equipment for cooking using gas stoves, that would eliminate a number of difficulties encountered while cooking, and provide a much more comfortable experience, especially in Indian domestic kitchens. This serves as an example to comprehend how to apply product
development processes and methodologies, and would enable the reader to bring out quality products of their will. In the latter stages, the product design has been validated using analysis by CFD, to demonstrate its superior performance. The product has been holistically defined by providing its geometrical measurements and a consolidated Bill of Materials table. One pointer with relation to the flame shield that might house scope for future iterations is that one flame shield can only employed on a single burner at a time, and if suppose the user requires a four-burner stove, they would need to purchase four of these products. Further work could be done in order to arrive at a concept that might obviate this minor possible improvement. It is hoped that our paper proves to be fruitful to fellow designers and researchers on the lookout for new product development techniques and their applications.

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