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Effect of Rectangular Fins on Heat Transfer Characteristics of Domestic Cookware

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ABSTRACT

Working process of domestic gas stoves primarily depends on the heat transfer phenomenon between gas flame and the bottom of the cookware. Various energy losses during this heat transfer results in low thermal efficiency. This work focuses on improving heat transfer ability of cookware, thus enhancing thermal-efficiency. Increase in rectangular fin height H causes increase in thermal efficiency value up to a certain limit after which a decreasing trend is observed by both numerical and experimental results. The fin height H=14.6 mm is considered optimum value for thermal efficiency. After H=14.6 mm, the maximum temperature value of fins shows a constant trend up to certain limit. Fin width variation follows a linear increase trend as the width increases up to 5 mm where fluctuation in efficiency stops. Max temperature of fins shows good agreement with increase in fin width in both numerical and experimental values up to W= 4.8 mm after which 10c temp loss occurs due to localized heat losses. Lastly fin spacing is verified against overall thermal efficiency and gradual; decrease is found in efficiency with increasing spacing due to formation of hotspots in between each fin. Lowest efficiency of 57% observed at fin spacing of 7 mm.

1. INTRODUCTION

From ancient ages, energy remains as the foundation for the continuous evolution and development of living things on earth, which gives rise to the developed human era nowadays. This energy in the form of LPG needs to be saved and conserved as it plays a vital role in cooking methodology all over the globe. Enhancing the ability of cooking in general cookware finds a crucial place in today's context. Wang et al. [1] done the investigations on enhancing the ability of cookware by adding fins on base of wok and observed that when 42 fins are considered for study, overall efficiency of cookware wok is enhanced by approx. 8% from the basic simple cookware which is without such heat exchange surfaces. Their experiment results hold good agreement with numerical. Wae-hayee et al. [2] studies the effect of distance between plate and burner on LPG consumption and heat transfer. They found the highest heat transfer rate at H/d between 25 and 35, KB-5 LPG burner is employed in this work by the authors. Bansal et al. [3] focusses on current status of the technology used in five major household equipment for the sake of energy savings and proposes founding minimum performance standards for all cooking appliances based on their rating and also asked for government initiatives in this undiscovered field of cooking where availability of government authorities puts check on overall energy utilization scenario in market. Boggavarapu et al. [4] done the comparative study of different burners using LPG as a fuel and done comparative study with PNG fuel burner by considering factors like loading height, and found augmentation in thermal efficiency of burner of about 2.5% when burner uses LPG along with modification, and 10% for burner using PNG as a fuel, their numerical simulation results found good agreement with the experimental one. The paper [5] studied the performance on cooking pots and evaluated their thermal efficiency on electric stoves. Author's experimental and numerical results found with a difference of not greater than 15% for all geometries evaluated. Adding insulating materials to cooking pots on electric stoves reduces losses up to 6.64%. The average thermal efficiency value of the electrical stove top enhances up to approx. 87% when they add outer insulation to the cookware.

2. UNCERTAINTY ANALYSIS

Uncertainty analysis is done by Pointing out uncertainty value & writing down value at midpoint of uncertainty interval along with difference to upper and lower limit. Experimental measurements are done using equipment with following accuracies: The water temperature, mass of water & consumed gas volume is ± 1℃, ± 2 gm., and ± 1.62 kg respectively.

3. EXPERIMENTAL SETUP

Figure 1 shows overall arrangement of test methodology setup used in the experimentation process. Waghole et al. [6] clearly mentions the usage of water as a better heat transfer fluid for experimentation of different heat transfer characteristics. In this experimentation, water at room temperature is to be allowed to test due to its better heat conductivity compared with other mediums which are costlier and impracticable for use in kitchen cookware otherwise. This water is used for Performing water boiling tests. Flow rate of gas which is required to be measured for efficiency calculations are to be measured with the help of soap bubble meter which are previously calibrated and set at standard NTP conditions. Mercury standard thermometer is used for measuring water temperature which is located at center of water pool for uniform temperature measurement and it measures the range of changing water temperature from room temperature up to boiling point of water calculated at local altitude height as well as total time required in seconds during this entire range. Digital data logger connected with personal computer is used to monitor and record the temperature noted down by the thermocouple. Overall Thermal efficiency of given cookware is deduced by dividing output energy obtained in cookware by the input energy supplied by a LPG cylinder. LPG flow rate is measured with help of bubble flow meter and is taken in the range of 9.72 ml/s to 20.83 ml/s. For each flow rate experimentation is carried out. Cookware used in this experimentation is of structural steel high grade. Total LPG consumption is noted by measuring initial and final weights of the LPG cylinder using a Heseley digital weighing machine. Pressure is regulated by pressure reducing valve and set as per domestic consumption standards [7].

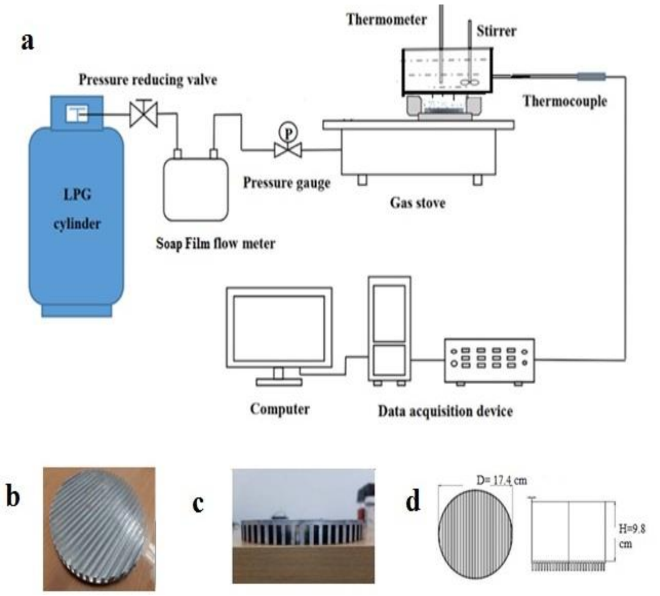


Figure 1. a) Experimental setup. b) Machined Rectangular Fins. c) Side View of Fins. d) Overall dimension (Height & Diameter)

$$\dot{\eta}=[m_w*c_p*(t_f-t_i) + m_{w,evap} * h_{fg}] / (m_f *c_v)$$

An overall thermal efficiency of any cookware described as per BIS catalogue is calculated by using above formula where output is taken as summation of enthalpies of water contained for heating along with total mass of water evaporated during WBT test. Here input to the system is taken as calorific value of fuel in combination with mass of fuel consumed during entire heating process for combustion.

4. NUMERICAL ANALYSIS

The computational analysis carried in this experimentation aims to augment the heat flow capacity of the cookware by monitoring temperature distribution &variation in one directional heat flux throughout the cookware, thus resulting in its improved thermal efficiency. Numerical computational method permits us to model and augment available products within prescribed time frame. In the actual process, water in the cookware boiled gradually with the time and its temperature is noted, and finally, at the end of saturation level the final temperature is noted, which we called as boiling phenomenon. Geometric modeling is done in solid works software where a detailed model is obtained which is then imported to Ansys for numerical simulation. The simulation process in this work considers single domain with steady state thermal boundary conditions as its quite easier to study such complex geometry with convenience in computational time. Cookware geometry as a single domain is considered for simulation to avoid unnecessary wastage of computational sources and time. High-grade Stainless-steel properties and minimum as well as maximum temperatures occurred during entire process were feed as boundary conditions for the simulation purpose.

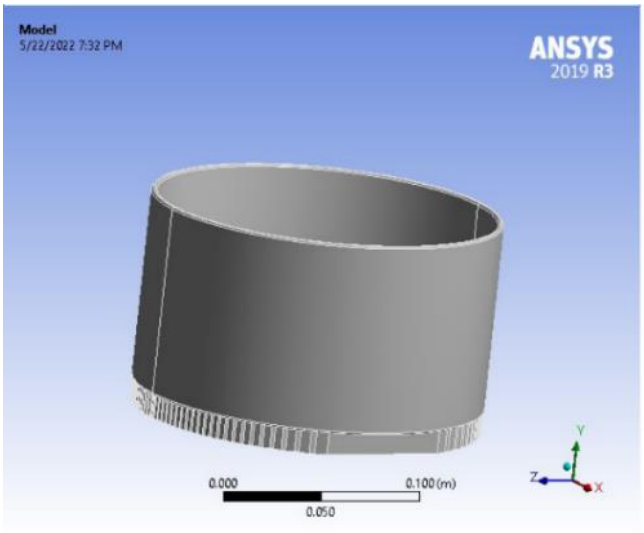
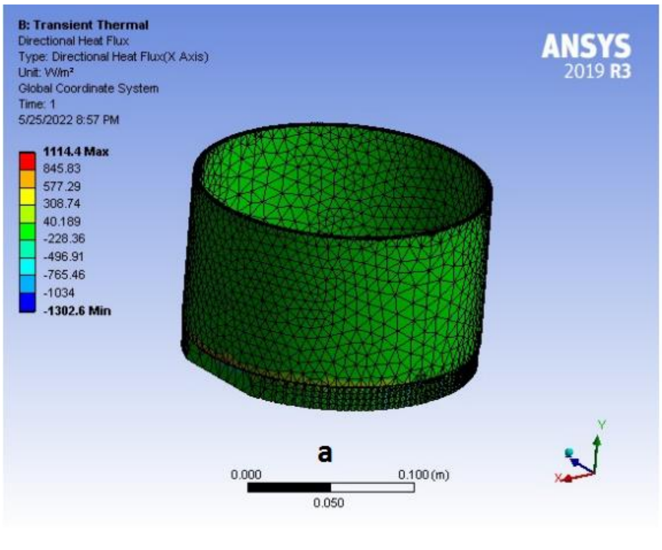


Figure 2. Geometric model diagram (Left side view)

Figure 2 shows the Geometric modeling of cookware used for experimentation in water boiling test and its modelling is done in solid works software where a detailed model is obtained which is then imported to Ansys for numerical simulation.



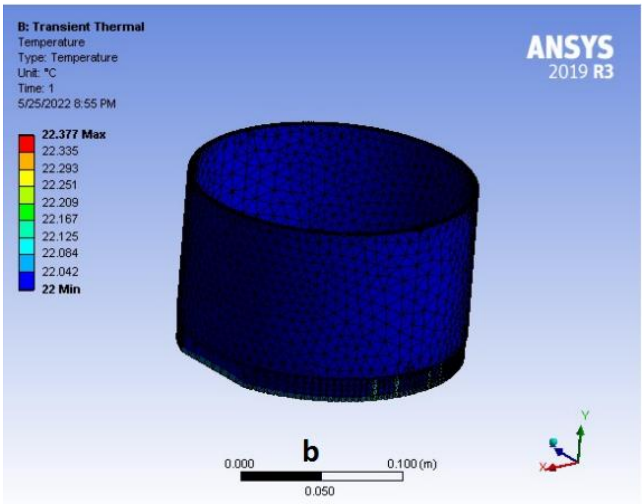


Figure 3. a) Heat flux b) Temperature distribution in model 4

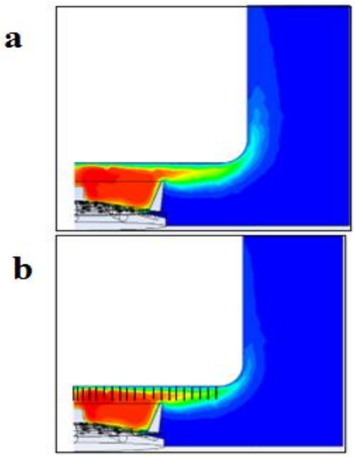


Figure 4. Flame propagation and local temperature distribution in (a) plain base b) Finned base

Figure 3a shows the directional heat flux distribution for model no.4 taken for numerical analysis consideration where uniform distribution occurs in agreement with experimental values. Whereas Figure 3b indicates time step distribution of initial temperature to be supplied during starting of experimentation. Here minimum time step is considered to be 1 sec period over which variation of temperature is observed and numerically it shows linear relation as compared to other models. Here cookware heats up uniformly.

Figure 4 indicates flame regulation due to adding of fins at bottom of cookware. In Figure a clearly its visible that when pot bottom is simple without any obstruction in path of flame, the peripheral flame propagates outside the base and some het gets lost in surrounding atmosphere whereas Figure b depicts installing fins at bottom which creates obstruction to free flame propagation outside the diameter of pot and kept it concentrated to bottom.

Geometry selection is considered here to be scoping method. All bodies are considered as geometry. Global coordinate system is implemented. Minimum temperature range at boiling point is set to be 99.9830c, whereas maximum is set at 101.070c. Boundary conditions: Heat flux at the bottom surface: it depends on gas burner range, here 4550 btu gas burner = 1285 watts of power, assume constant heat flux load of 1000 w/m^2. Free convection air temperature: 291 K, Initial water temperature: 295 K.

A thermal analysis calculates the temperature distribution and related thermal quantities in a system or component. Transient thermal analyses determine temperatures and other thermal quantities that vary over time.

Step Controls: Step Controls enable to control the rate of loading which could be important in thermal analysis if the material properties vary rapidly with temperature.

When such nonlinearities are present it may be necessary to apply the loads in small increments and perform solutions at these intermediate loads to achieve convergence.

A transient thermal analysis involves loads that are functions of time.

The first step in applying transient thermal loads is to establish the initial temperature distribution at time = 1 sec.

Initial temperatures do not matter in steady-state analyses.

Initial temperatures are very important in transient analyses. Here, Time step is the incremental change in time for which the governing equations are being solved. It is advised from literature to select small time step size to capture all the transient fluctuations. If the dynamics of the system is slow/low frequency, then we should assume larger time step whereas if the system contains very rapidly responding elements, then we need smaller step to track those accurately. Figure 3a and 3b shows uniform one directional heat flux distribution identified in model no. 04 by numerical simulation and validated by experimental results.

5. RESULT AND DISCUSSIONS

5.1 Effect of fin height

Das et al. [8] Explains with their experiments that when there is increase in loading height Z between burner flame and base of cookware, the thermal efficiency predicted decreases gradually. After addition of fins to the cookware, it is general observation that the thermal efficiency of the cookware gradually increases with an increase in fin height H up to certain value. We have considered range of 11.7 mm to 15.5 mm height for rectangular fins attached at bottom of cookware. For each respective height the thermal efficiency calculations were done by employing water boiling test and final values are deduced. It has been found that up to 14.6 mm height of fins unit increase in percentage efficiency observed while height goes to 15.5 mm, a declining trend starts and drop of 0.30% occurs which can be neglected in error.

Figure 5 shows relation between fin height and thermal efficiency of cookware by considering five different values if height of rectangular fins ranging from 11.7 mm to 15.5 mm. Fin height shows linear trend and act as heat absorption surface area up to 14.6 mm due to which maximum achievable temperature of 376.55 k is obtained in fin surface area which is slightly above the standard boiling point calculated for water at local altitude. But after 14.6 mm slight decline is observed in thermal efficiency due to heat retention behavior. Loading height of cookware works as same parameter like that of the height of fins attached at the bottom. As previously found when we increase height of fin gradually, thermal efficiency steadily increases, this same trend was found in good agreement for loading height parameter also. Up to 24 mm height the efficiency increases linearly after which the flame loses its intensity and hot gases get deviated from path causing decline in thermal efficiency.

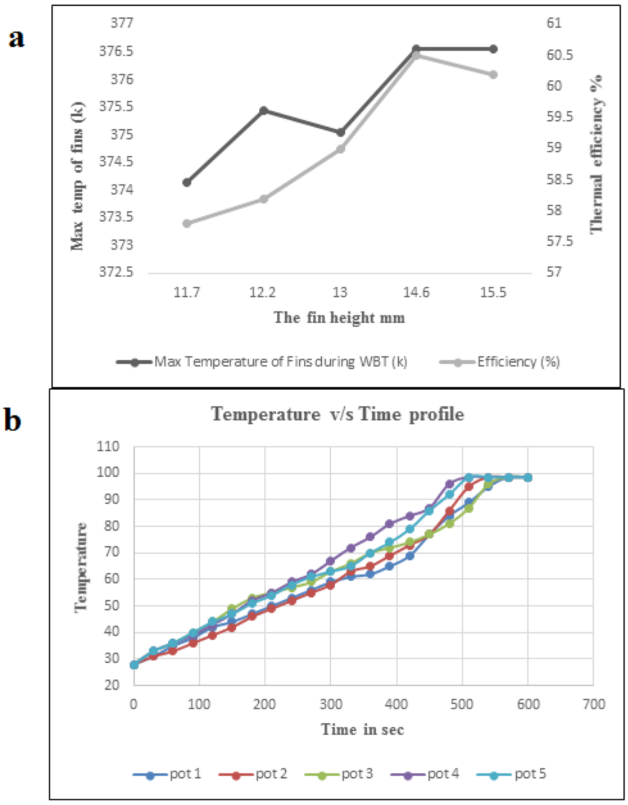


Figure 5. a) effects of fin height on thermal efficiency and maximum temperature of fins b) effects of fin height on Temp v/s Time Profile

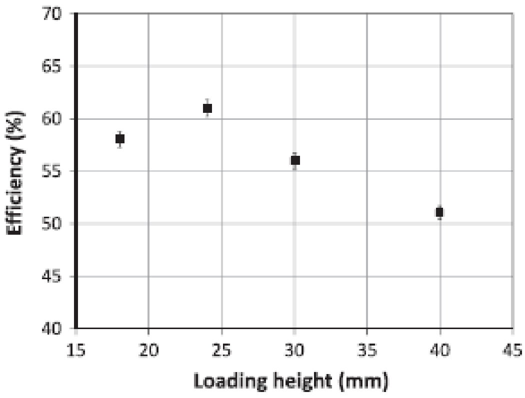


Figure 6. Effect of loading height on cookware thermal efficiency

Figure 6 shows relation between loading height of cookware from the burner flame with its performance. Efficiency value almost reaches maximum at 25 mm loading height after which it starts declining with increase in heights of stand on which cookware is placed above burner.

5.2 Effect of fin width

Fin width or thickness of fin plays crucial role in retaining or dispersing the heat to environment. Figure 7a and 7b clearly mentions the overall effect of fin width on performance of cookware. Even when we consider cookware with thin bottom layer compared to thick one, hot spots or scorching of food phenomena takes place more prominently. Here thermal efficiency for cookware gradually increases from 58.8% for 2.5 mm thickness of fin up to 65% for 5 mm thick fin area. This clearly shows that thicker material retains heat more uniformly without creating hot spots on bottom. Tatsuguchi and Shibukawa [9] clearly demonstrates that Cookware which are thin in base or had low thermal conductivity had an uneven temperature distribution throughout the bottom area and has more tendency to get scorch.

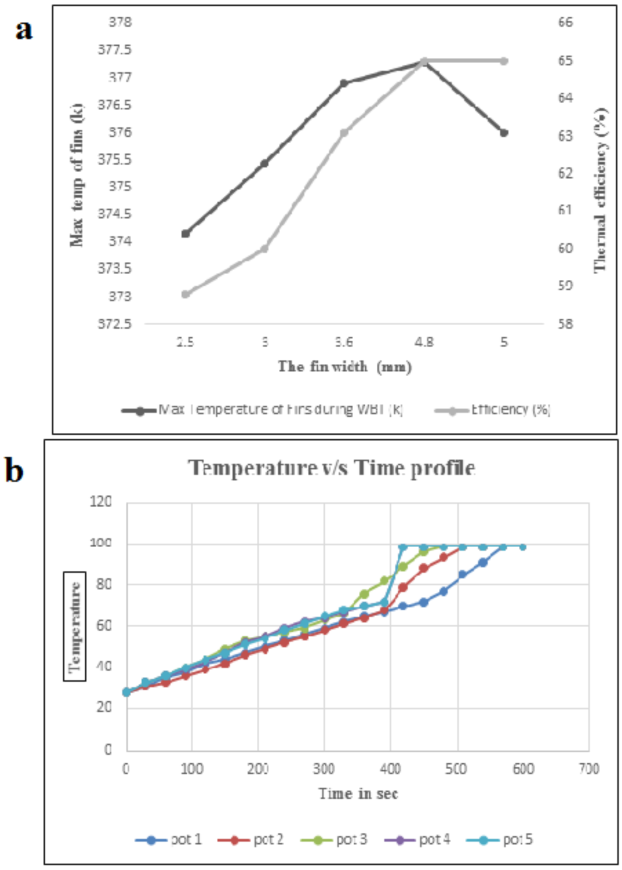


Figure 7. a) effects of fin width on thermal efficiency and maximum temperature of fins b) effects of fin width on Temp v/s Time Profile

Another parameter we have to consider here is temperature drop for fins. From literature survey, we conclude that decrement in temperature is proportional to thickness of material, and inversely proportional to the thermal conductivity. Figure 7b shows cookware 5 showing liner temperature time profile on all temperature ranges from start to end. Same behavior was observed when we go on increasing thickness of fins beyond certain value. At 5 mm fin width if we continue further then an approx. 1°C drop in max temp of fins were observed.

5.3 Effect of fin spacing

When we add more and more fins, it ultimately provides greater surface area, and hence more heat is transferred to the cookware [10, 11]. As the fin spacing increases the surface area exposed directly to flame increases widely which may cause scorching of food or developing hot spots frequently on base area. As we increase fin spacing from 3.72 mm to 7 mm, maximum drop in thermal efficiency occurs due to reduction in effective heat transfer area and easy escape of flue gases to atmosphere leading to heat loss in outer environment.

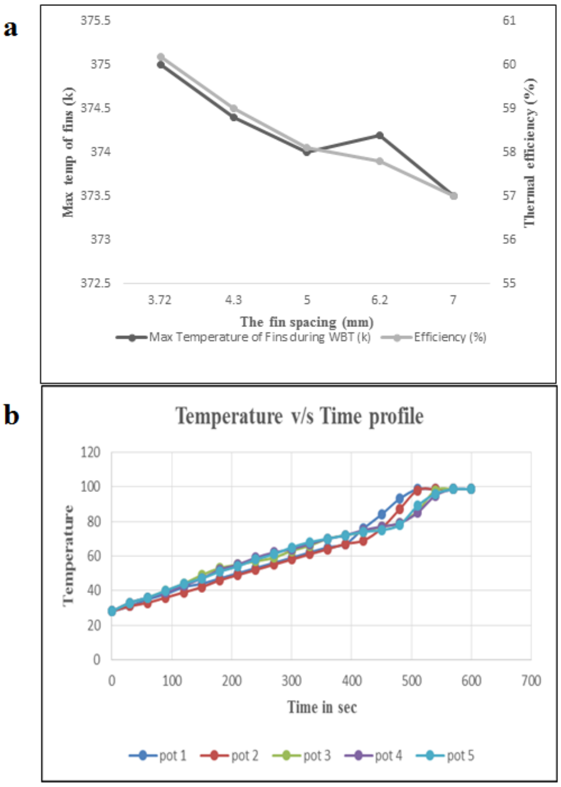


Figure 8. a) effects of fin spacing on thermal efficiency and maximum temperature of fins b) effects of fin spacing on Temp v/s Time Profile

In above Figure 8a, fin spacing shows nonlinear impact on thermal performance of cookware. As fin spacing increases, the efficiency of cookware goes on decreasing to larger extent due to uneven bottom heating and hotspots. Figure 8b reflects the same behavior of cookware in terms of temperature time profile as seen in Figure 8a.

5.4 Effect of miscellaneous parameters on cookware performance

With reference to fin spacing the area of utensils also affects the overall performance, increase in utensil size; there is increase in LPG consumption as surface area for heating increases. It is connected with the increased radiation and convective heat losses from the larger utensil exposed surface [12]. There can be improvement in efficiency by just Changing the utensil size and the cooking routines (i.e. use of low flame condition when not urgently required in spite of high flame condition) [13, 14]. It can be also deduced that more than 15.2 kg of LPG which is equivalent to one LPG cylinder can be saved annually by just using utensils of optimum aspect ratio, at low flame condition [15, 16]. Variable gas flow rate provides freedom to control amount of Heat supplied to the various foods [17]. Different utensils behave differently at each flow rate. A linear relation is observed between flow rate and gas consumption for each type of utensil.

6. CONCLUSION

Experimental and numerical analysis was done to investigate heat transfer characteristics in rectangular fin surface geometry when used in cookware. This study shows that usage of rectangular fins on cookware bottom increase heat transfer. From this experimental work, the findings are as follows:

1 Fin height clearly indicates two things, first increased surface area resulting in enhanced heat rate and second is distance between cookware bottom and flame leading to decreased efficiency when fin height goes beyond certain value. Highest value of thermal efficiency 60.5% and maximum temperature of fins 376.5 k are obtained at height of 14.6 mm after which it doesn't maintain linear relation. Fin height is considered to be optimized at 14.6 mm.

2 For fin width parameter, overall thermal efficiency for cookware increases from 58.8% for 2.5 mm thickness of fin up to 65% for 5 mm thick fin area. This clearly shows that thicker material retains heat more uniformly without creating hot spots on bottom.

3 Thick area distributes heat more uniformly thus 4.8 mm thick fin is considered optimized fin width for energy efficient cookware.

4 More spacing in fins indicate plainer bottom open to flame directly resulting in creation of uneven heating. We observe gradual increment in thermal efficiency value when spacing between fins reduces from 7 mm to 3.72 mm. This clearly indicates inverse relation between fin spacing and energy efficiency of cookware.

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