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An Experimental Study on the Effect of Thermal Shield on Energy Saving in Cooking Pot

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Abstract
The present study aims at reducing the energy consumption in the cooking process by using a simple technical method, a thermal shield around the cooking pot. The research has conducted experimentally and the effect of the thermal shield on the thermal efficiency was investigated regarding the geometric parameters of the pot (diameter and height) and the amount of fluid in the pre and post-boiling stages. The results showed that the thermal shield has a positive effect on pre-boiling stage leading to an average amount of 20% energy savings independent of geometry and the amount of fluid. It was also shown that the effect of thermal shield in the boiling stage is a function of liquid height inside the container. Also, for a constant value of thermal energy, the effect of thermal shield increases with the container height without limitation. It was also shown that the effect of the thermal shield in boiling stage is a function of the height of liquid inside the container. Finally, an economic investigation for Iranian households showed that utilization of a thermal shield in cooking process will save energy consumption equivalent to 12.5 million barrels oil per year.

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Cooking Pot
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Energy Consumption
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Fossil Fuel

Introduction
Energy savings has become one of the critical international policies in the field of research and management. The limitation of fossil fuels, the pollution resulting from using these fuels, and the impact of political changes on energy resources are some of the important parameters in this area. A lot of researches have been devoted to improve the energy consumption pattern in various fields, annually. Part of research in this area is performed with the purpose of facilitating the transition of energy resources from fossil fuels to renewable energies; some other research has been focused on the optimization of fossil fuel and renewable energy consumptions. Also, several researchers have focused on the energy recovery in order to design and implement approaches to recover a part of energy loss in thermodynamic systems. Generally, energy consumption optimization is a strategic policy in both global and national scales. Besides considering the energy consumption quality, a significant portion of efforts

has been devoted to hazard elimination, increasing the system efficiency, and decreasing the production of carbon oxides. According to the literature, more than 30% of energy consumption is related to the household energy use 80% of which is associated to cooking (Moshiri *et al*., 2011). In some research it has been reported that up to 90% of household energy consumption is attributed to cooking in developing countries (Nahar & Gupta, 1991). Thus, the considerable growth in solar cookers can be attributed to this fact, because these systems provide the possibility of using the solar energy for cooking instead of fossil fuels (Panwara *et al*., 2011). In this regard, other renewable energies such as biomass have been taken into consideration (McKendry, 2002). Based on the considerable contribution of fossil fuels in this area, a great deal of researches have been carried out to reduce the energy consumption in cooking process; for instance, increasing the heat transfer surface in cooking pots or cook stoves. In less developed regions, plans for utilization of green energy in energy-efficient stoves have been proposed (Thacker *et al*., 2017). Also, in developing countries, as a result of sustainable development, pots equipped with thermal shield are used to save thermal energy as much as possible (World Bank, 2014). Despite the existence of several studies in the area of optimal energy consumption in cooking pots, investigating the utilization of thermal shields both experimentally and numerically is increasingly attracting attention. Using an appropriate cooking method not only should successfully resolve the high energy consumption and production of environmental pollutants challenges, but also has to be consistent with the cooking local traditions. Various studies have proven that the three sides of an ideal cooking, that is optimal energy consumption, minimal production of pollutants, and consistency with cooking traditions, can be assumed as functions of the pot shape, the heat transfer mechanism to pot, and the energy source. Thus, the proper variables of cooking system can be defined. Many researchers have focused on the simultaneous effect of geometry and heat transfer mechanism to the pot in order to achieve an optimal cooking process. In this regard, Cadavid *et al.* (2014) have simulated the thermal efficiency of a pot as a function of geometrical properties (height, diameter and material) via an experimental-numerical approach using ANSYS-fluent software. Their results showed that the best thermal efficiency was related to a pot with shortest wall and largest diameter. Also, Hannani *et al.* (2006) have mathematically investigated the effect of the pot diameter, corner angle, and wall slope on the thermal efficiency using neural network algorithm. They showed that increasing the pot diameter, bottom wall curvature and pot wall slope leads to an increase in thermal efficiency. Also, their results showed that increasing the ratio of pot diameter to pot height improves the thermal efficiency. According to the obtained results, the height of cooking material in the pot has an insignificant impact on the quality of heat absorption. In addition to the pot geometry, the cooking traditions directly affect the thermal efficiency; for instance, closing the lid during cooking, using all the volume of container and utilization of thermal isolation can decrease the energy consumption. Also, in addition to the thermal efficiency which is a function of pot geometry, the amount of pollutant production may be effectively reduced by properly designing the pot

(Karunanithy & Shafer, 2016). For this purpose, one can refer to Arora *et al.* (2014) wherein three modern technologies of high efficiency cooking are compared with the traditional brick-mud cook stove; the obtained results showed that the carbon monoxide emission was reduced in modern cook stoves. Arora *et al.* (2014) have evaluated the effect of chemical components and humidity of fuel on the thermal efficiency. Furthermore, the quality of heat transfer to cooking pot has been considered as a key factor in optimization of cooking process. In this regard, Kanjanapongkul (2017) has used ohmic heating to uniformly cook rice. They compared the performance of ohmic heating with other modern devices such as electric rice cooker and microwave. Daioglou *et al.* (2012) have investigated both induction and natural gas cook stoves' pot to optimize the geometry and material of pots and propose novel designs. In addition to above mentioned research, which studied the effect of pot geometry, heating mechanism, and traditions related to how a cooking pot is used, some other studies have been devoted to the proper cooking standards in underdeveloped areas, rural and suburb areas. Regarding the fact that the fuel used in these regions is highly polluting, the main focus of research has been on the optimization of burning process in cook stoves. It should be mentioned that approximately around one-third of world population does not have access to proper cooking devices with low level of pollution production. It seems that this ratio does not change until 2030, (MacCarty *et al.*, 2010). Burning the biological materials leads to emission of hazardous pollutants including carbon monoxide, nitrogen oxides, phosphor oxide and other airborne particles jeopardizing the human health (WHO, 2016). In the last decade, considerable amount of effort has been taken in developing countries to develop biomass cook stoves. According to the fact that almost 3 billion people around the world are still using fire or wood fuel, charcoal or other solid fuel cook stoves, a genuine motivation has been created in this research area (WHO, 2016). Utilization biomass cook stoves have been considered as one of global warming factors. Around 22% of airborne soot particles are produced because of burning biomass. However, fossil fuels only produce 7% of total soot. Previous studies showed that the adverse effect of biomass burning is the cause of death of around 3 million people in the world, annually (Kshirsagar & Kalamkar, 2015). The biomass cook stove performance improvement plan focuses on the reduction of pollutant emission in indoor environment, reducing the production of greenhouse gases, and efficient use of fuel. Based on these efforts, a considerable improvement has been achieved in the areas of thermal efficiency and cleanliness standards (Kshirsagar & Kalamkar, 2014; Funk, 2000). In the present paper, the effect of thermal shields on thermal energy absorption efficiency for cooking pot in an axial natural gas fueled cook stove is investigated, experimentally. The idea of using a thermal shield to improve the heat absorption in the pot can be a proper approach to achieve a fast and cheap cooking process. Therefore, the main innovation of present study is to propose a simple approach to reduce the household energy consumption and analyzing its influence in national scale.

Problem description

In present study, the thermal energy absorption efficiency in a pot equipped with thermal shield and containing water is investigated. According to Figure (1), the mixture of fuel and warm air move in the radial direction and transfer the heat to the central and other areas in the bottom of container. Next, the low energy flow of combustion gases and hot air moves toward the pot edge. Utilization of thermal shield results in reduction in thermal energy loss to the ambient and thus increases the quality of heat absorption by the container. In the present paper, the effects of geometric parameters including the pot diameter, pot capacity, and also the height of water inside the container on the thermal efficiency in two stages; before and after boiling are investigated.

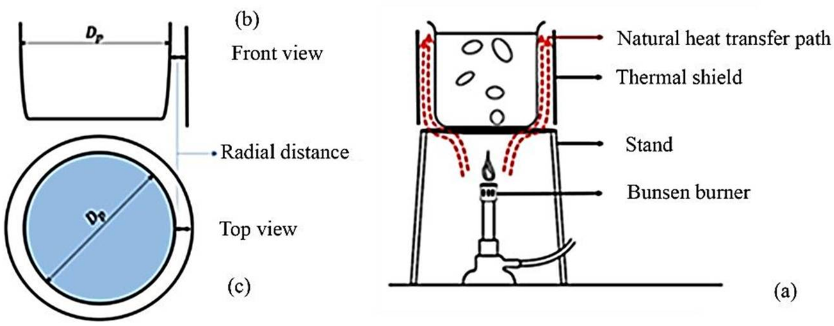

Figure 1. (a) The schematic representation of water heating including the container, thermal shield, stand, and Bunsen burner, and (b and c) Two dimensional views of thermal shield and the container

Figure (2) demonstrates the experimental apparatus including the gasometer, Bunsen burner, and pot with thermal shield.

Figure 2. The experimental equipment including gasometer, Bunsen burner, and double wall container

Material and methods

In order to investigate the effect of geometrical parameters of container, three steel pots were used with diameters of 19.4, 24 and 29.3 cm and total volumes of 1750, 3500 and 5500 mL, respectively. Also, as shown in Table (1), the various volumes of water are used. A household cook stove equipped with gasometer is used for heating. For the first step in each experiment, a simple container with known volume of water is employed and the results are recorded for two stages. In the first stage, the variations in temperature are recorded until the water reaches the boiling point. Then, the amounts of evaporated water and consumed fuel were recorded in a period of 10 min. In second step, similar to previous stage, the experiments were performed with the aim of investigating the effect of thermal shield on the value of energy absorption as a function of container capacity and the volume of water inside the pot. However, in the second step, the criterion for end of experiment was considered to be the time when the consumed fuel was equal to the one in first stage.

Table 1. The experiments conducted on the various pots

Type	Performed experiments based on the volume of pot (mL)									
Large		500	1000	1500	2000	2500	3000	3500	4000	4500	5500
Medium		500	1000	1500	2000	2500	3000	3500			
Small	250	500	1000	1500	2000						

Because of the oscillation in flow rate of urban gas pipelines, using this method can minimize the difference between energy consumed for warming water in simple containers and the ones equipped with thermal shield.

Accuracy of measuring devices

The ambient temperature T_a was measured by testo 605 thermometer with an accuracy of ±0.5 °C. The temperature of water in the container was measured using a two-channel testo 922 thermometer equipped with k-type thermocouple (NiCr-Ni) with accuracy of ±0.5 °C+0.3% mv. According to the international standards, the thermocouple sensor should be located inside the water and 5 cm upper than the bottom of container (Funk, 2000). The natural gas flow rate was measured by a laboratory flow meter, VINCI, WG series. The flow meter capacity in each round was 25 dm^3, the flow range was 30-90 l/h, and its accuracy was ±0.5%. This flow meter worked in ambient pressure and temperature conditions. In order to investigate the effect of thermal shield on the quality of energy absorption, a thermal efficiency parameter for containers with thermal shield was defined. Then, an overall estimation of energy saving was made to investigate the amount of resultant energy savings if this approach was used publicly.

Result and discussion

The performance of thermal shield before boiling

The relationship of heat transfer to a single-phase substance can be written as follows:

$$Q_{pot} = mc\frac{\Delta T}{\Delta t} \tag{1}$$

Where Q_{pot} is a part of combustion energy (Q_{com}) absorbed by the pot. Therefore, the above relation can be written in the following relation:

$$\dot{Q}_{pot} = \eta \dot{Q}_{com} \tag{2}$$

By assuming that the variation of temperature regarding time is linear, thus for a specific increase in water temperature (ΔT), a constant rate of thermal energy production (Q_{com}=*cte*), and a specific mass of water (*m*), the efficiency of thermal energy absorption (η) can be written as follows:

$$\eta = \frac{mc}{\dot{Q}_{com}}\frac{\Delta T}{\Delta t} \tag{3}$$

To quantitatively define the thermal value of using a thermal shield, the efficiency parameter (ε) can be expressed as the ratio of difference between energy absorption efficiencies in a pot equipped with thermal shield and a simple pot to the energy absorption efficiency of the simple pot; thus:

$$\varepsilon = \frac{\eta_{sh} - \eta_{si}}{\eta_{si}} \tag{4}$$

or

$$\varepsilon = \frac{\Delta t_{si}}{\Delta t_{sh}} - 1 \tag{5}$$

Where Δt_{si} and Δt_{sh} are the times when the temperature reaches to 93 °C in simple and shielded pots, respectively. It is obvious that if the thermal shield effectively manages the thermal energy absorption, the time period of achieving a specific temperature in shielded pot becomes less than in simple pot. Figure (3) shows the variations of ε as a function of pot size and the volume of water content in the pot. According to Figure (3), one can deduce that in the pre-boiling stage, the utilization of thermal shield results in 20% improvement in quality of heat absorption. Also, Figure (3) shows that there is no meaningful correlation between pot geometry, water content, and the quality of energy absorption. In fact, employing a thermal shield in pre-boiling stage always guaranties a 20% increase in thermal energy absorption. The obtained results from the experiments are consistent with the previous reports in which utilization of thermal shield was accounted as an effective factor to reduce the fuel consumption by 25-30% (MacCarty *et al*., 2010).

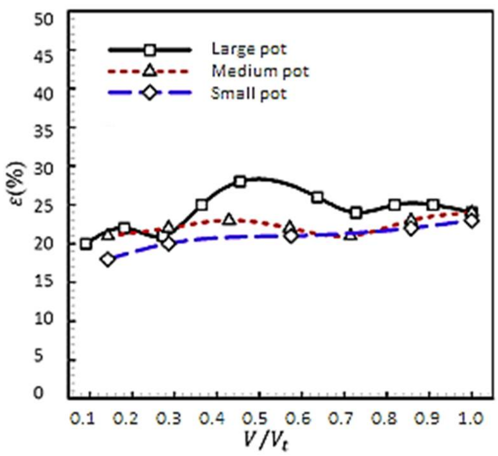

Figure 3. The variations of energy absorption quality as a function of water content volume to pot capacity

Performance of thermal shield in boiling stage

In order to examine the effect of thermal shield on energy absorption in boiling stage, another efficiency parameter should be defined. The heat transfer relationship in boiling stage can be written as follows:

$$\dot{Q}_{pot} = \dot{m}h_{lv} \qquad (6)$$

Where h_{lv}, is the latent heat of vaporization and m is the evaporation rate. Using Eq. (4), the efficiency parameter of thermal shield in boiling stage can be written as.

$$\varepsilon = \frac{\dot{m}_{sh} - \dot{m}_{si}}{\dot{m}_{si.}} \qquad (7)$$

For a known period of time from the time boiling has started, Eq. (7) can be written as follows:

$$\varepsilon = \frac{\Delta m_{sh}}{\Delta m_{si}} - 1 \qquad (8)$$

Where Δm_{si} and Δm_{sh} determine the evaporated water in simple pot and the pot equipped with thermal shield, respectively. The more effectiveness of the thermal shield reduces the thermal loss from the pot, the more increase in the ratio of $\Delta m_{sh}/\Delta m_{si}$ is achieved and thus the efficiency of thermal shield increases. In order to analyze the effect of thermal shield on the heat absorption in boiling stage, the amount of water evaporated in 10 min as a function of pot diameter (with pot capacities of 1750, 3500 and 5500 mL), the height of material inside the pot (according to table 1) is calculated for both simple and shielded pots. The results of all 44 tests are presented in Figure (3). In Figure (3), the efficiency parameter is drawn as a function of pot size and the characteristic height. The characteristic height can be defined as follows:

$$H^* = V_w/A_{pot} \qquad (9)$$

Where V_w and A_{pot} are the volume of water and the bottom area of cylindrical container, respectively. As it can be seen in Figure (3), in contrast with the pre-boiling stage, there is a meaningful correlation between the efficiency parameter, the height of liquid and the size of container. According to Figure (3), except for the specific interval of 2cm≤H*≤3cm in which the influence coefficient decreases with increasing the volume of liquid, increasing the liquid volume, and especially around to the ultimate capacity of the pot, leading to a linear and homological (in all dimensions of the container) increase in pot's influence coefficient. The decrease in influence coefficient in a specific interval of liquid height can be attributed to the concentration of temperature distribution along the thermal boundary layer developed between two concentric cylinders. In the space between the thermal shield and the pot. In fact, at constant value of roughness in the interface of solid-fluid and at constant ambient pressure, the energy absorption in nucleate boiling depends on the number of active bubble formation points. The temperature concentration points with the potential of bubble formation can lead to activation of these points and alternative formation of bubbles. Possibly, for the liquid height between 2 and 3 cm, the concentration points of heat transfer to the pot are located in the points where the hot gas enters into the annulus space between two cylinders and also at the top of this space where there is no contact between the liquid and the wall. Therefore, in a specific interval near the free surface, the bubbles could not be formed in proportion with increase in height of the liquid. In fact, because the wall roughness is constant, in order to maintain growth trend of energy absorption coefficient as a function of liquid height similar to the interval of zero to 2 cm, the number of potential points for the bubble formation should increase in proportion with increase in volume of water. It is possible that in the mentioned interval, the growth in energy absorption coefficient did not occur because of the location of heat transfer concentration. When the liquid height passes the critical interval (2cm≤H*≤3cm), according to Figure (4), it can be inferred that for a specific thermal energy, because of the presence of thermal shield, increasing the size of pot results in a decrease in the energy loss.

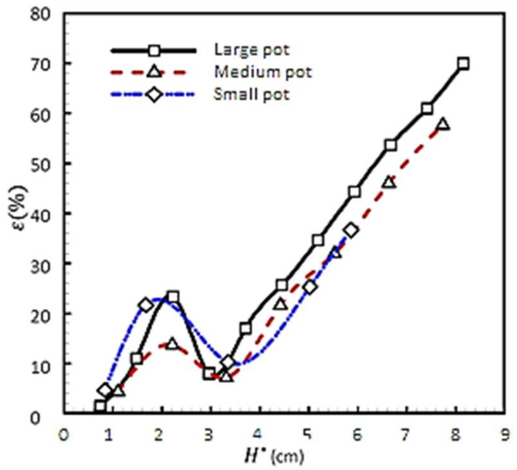

Figure 4. Variations of in influence coefficient (in percentage) as a function of characteristic height for different pots

According to Figure (4), in order to achieve an optimal performance of thermal shield, the height of materials inside the pot should be larger than a specific value (here, 3.5 cm). For this purpose, the amount of water inside the pot should be increased or for a small volume of material a smaller pot should be used.

Investigation of the economic efficiency of thermal shields

Moshiri *et al.* (2011) performed a research in the field of allocation of national energy resources and prediction of energy demand in Iran. They calculated the energy consumption per family for the time period of 2005 to 2030. The results were shown in Table (2), which included the details of household demand for energy based on various types of energy resources.

Table 2. The information of household energy consumption for various type of energy resources (2005-2030)

Energy Resource	Share (%)	2005 mboe	2030 mboe	Growth (%/yr)
Kerosene		47	113	0.97
heating	0	0	0	
Cooking	100	47	13	
Water heating	0	0	0	
Gasoil		8	13	2.11
heating	80	6	0	0
Cooking	0	0	0	
Water heating	20	2	3	
LPG		8	7	0.68
heating	0	0	0	
Cooking	50	4	3	
Water heating	50	4	3	
Natural Gas		197	559	4.25
heating	75	148	420	
Cooking	10	20	56	
Water heating	15	30	84	
Total (Oil and Natral Gas)		259.9	591.9	3.35
Solar			30	11.56
heating	1-5	0	21	
Cooking	1-5	0	4	
Water heating	1-5	0	4	

Based on the data presented in Table (2), the economic potential of using a thermal shield for high efficiency cooking pot can be investigated. According to Table (2), the consumption of natural gas, LPG, and kerosene for cooking in 2017 was equal to 33, 3.7 and 25.5 mboe, respectively. Therefore, utilization of thermal shield in cooking pots in 2017 could reduce the energy consumption to around 12.5 million oil barrels (approximately equal to 4 days of oil production in current time). This estimation has been made by assuming a 20% increase in thermal energy absorption in cooking process which only includes the process of warming the food. However, the cooking process involves the boiling stage. Considering the boiling process, using a properly designed thermal shield can increase the heat absorption more than 20% (according to figure 4, when the characteristic height is more than 5 cm).

Uncertainty analysis of experimental results

Uncertainty of each parameter in experiments might be due to the inaccuracy of measuring tools and repetition procedure which can be calculated as follows:

$$\sigma_v = \sqrt{\left(\sigma_{v_{equ}}\right)^2 + \left(\sigma_{v_{rep}}\right)^2} \quad (10)$$

The uncertainty for a multi-variable function such as k with variables of v_1, v_2, etc, v_n and v_m; and the calculated uncertainties of σ_{v_1}, σ_{v_2}, etc, σ_{v_n} and σ_{v_m} can be defined as:

$$k = \frac{v_1 \times v_2 \times \cdots v_m}{v_{m+1} \times \cdots v_n} \quad (11)$$

Where the uncertainties of parameters v_1, v_2, etc, v_n and v_m are independent. The overall uncertainty can be calculated as follows (Taylor, 1997).

(12)

$$\frac{\sigma_k}{k}=\sqrt{\left(\frac{\sigma_{v_1}}{v_1}\right)^2+\cdots\left(\frac{\sigma_{vm}}{v_m}\right)^2+\cdots\left(-\frac{\sigma_{v_{m+1}}}{v_{m+1}}\right)^2\cdots\left(-\frac{\sigma_{vn}}{v_n}\right)^2}$$

Because the purpose of experiments was investigation of the effect of container capacity and height of liquid on performance of thermal shield (Eqs. 5 and 8), the uncertainty of efficiency coefficient for Eq. (5) can be written as follows:

(13)

$$\frac{\sigma_{\varepsilon_1}}{\varepsilon_1}=\sqrt{\left(\frac{\sigma_{\Delta t_{si}}}{\Delta t_{si}}\right)^2+\left(-\frac{\sigma_{\Delta t_{sh}}}{\Delta t_{sh}}\right)^2+\ldots+\left(-\frac{\sigma_{V_{si}}}{V_{si}}\right)^2}=0.057$$

Accordingly, the uncertainty of efficiency coefficient in boiling stage can be written as:

(14)

$$\frac{\sigma_{\varepsilon_2}}{\varepsilon_2}=\sqrt{\left(\frac{\sigma_{\Delta V_{sh}}}{\Delta V_{sh}}\right)^2+\left(-\frac{\sigma_{\Delta V_{si}}}{\Delta V_{si}}\right)^2}=0.041$$

Table (3) presents the accuracy, type, and uncertainty of measuring tools employed in this study.

Table 3. Specifications of measuring tools and their uncertainty.

Parameter	Tool	Accuracy	Uncertainty
Volume	Graduated cylinder	±0.01 L	±0.01
Temperature	Thermometer Testo 922	±0.3 °C	±0.05
Time	Digital clock	±1 s	±1

Conclusion

In the present paper, the effect of thermal shield on the quality of thermal energy absorption in cooking pots at two stages; pre and post-boiling was investigated. The experiments were performed for three different pots with capacities of 1750, 3500 and 5500 mL. The water content in the pots was also considered as an essential parameter affecting the quality of thermal energy absorption. The results showed that in the pre-boiling stage, the effect of utilization of thermal shield on quality of energy absorption was not significantly dependent on the pot geometry and the volume of liquid inside the pot. Therefore, it can be argued that regardless of operational parameters, the thermal shield always has a positive effect on energy absorption. The calculations based on the experimental data showed that utilization of thermal shield increases the heat absorption by 20% approximately. However, in boiling stage, the effect of thermal shield depended on the characteristic height (the ratio of liquid volume to pot diameter) and was independent of container shape. Increasing the ultimate capacity of pot at a specific thermal influx can result in higher efficiency. Considering the fact that the main energy resource in Iran meeting the energy demand in the household cooking sector is fossil fuels such as kerosene, LPG, and natural gas with annual consumption of 25.5, 3.7 and 33 million barrel oil, respectively, using thermal shield can result in energy saving equivalent to 12.5 million barrel oil per year; that is equivalent to 4 days of Iran's oil sale in the global market. Based on the obtained results, using thermal shield for either warming the food or cooking in the stage of boiling is a simple and inexpensive solution for energy saving. This proposal can be commercialized in two following ways:

- To design thermal shields as cooking device accessories based on the dimensions of standard pots in the market;
- Gradually, reengineering the current pots and producing double-wall pots based on the idea of present paper.

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تحلیل تجربی اثر سپر حرارتی بر کاهش مصرف انرژی در ظرف پخت غذا

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چکیده

هدف این تحقیق کاهش مصرف انرژی در فرایند پخت و پز ازطریق استفاده از سپرهای حرارتی پیرامون ظرف غذاست. در این تحقیق که برای اولین بار و به‌صورت آزمایشگاهی انجام شده است اثر سپر حرارتی باتوجه‌به پارامترهای هندسی ظرف (قطر و ارتفاع) و مقدار سیال، بر بازده حرارتی قبل و بعد از جوشش مورد بررسی قرار گرفته است. نتایج این تحقیق نشان داد که در مرحلۀ قبل از جوشش استفاده از سپر حرارتی مستقل از هندسه و میزان سیال می‌باشد و می‌تواند به‌طور متوسط ۲۰ درصد انرژی مصرفی را کاهش دهد. همچنین نشان داده شد که اثر سپر حرارتی در مرحلۀ جوشش تابعی از ارتفاع مایع درون ظرف می‌باشد و برای یک مقدار مشخص انرژی حرارتی ثابت، با افزایش ارتفاع ظرف بدون محدودیت افزایش می‌یابد. درنهایت یک محاسبۀ اقتصادی برای خانوارهای ایرانی نشان می‌دهد که استفاده از سپر حرارتی در فرایند پخت و پز خانگی، موجب صرفه‌جویی در مصرف منابع انرژی گرمایی به ارزش ۱۲/۵ میلیون بشکه نفت در سال خواهد شد.

واژه‌های کلیدی: انرژی، سوخت فسیلی، ظرف پخت غذا، کاهش مصرف انرژی، مصرف انرژی