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NUMERICAL STUDY OF THE FACTORS THAT AFFECT THERMAL EFFICIENCY DURING INFRARED GAS STOVE HEATING

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ABSTRACT: The Energy Policy and Planning Office, Ministry of Energy, Royal Thai Government reported from 2007 to 2015, the using of fuel increase every year. In addition, price of fuel increases continuously. The way of most efficiently of energy using is important. This paper aimed to study about thermal efficiency of infrared gas stove by varies with parameters which were diameters of pot (220, 240 and 260 mm), distances between burner (20, 25 and 30 mm) and pot and diameter of burner head (135, 145 and 155 mm) in 9 cases by simulation method. The numerical model was validated with results from experiment in 220, 240 and 260 mm of diameter of pot, average errors are 10.85011%, 6.754703% and 2.13054%, respectively. The results of this study showed with three sizes of pot, huger distances between burner and pot decrease thermal efficiency. The highest thermal efficiency was in 260 mm of diameter of pot. All of 9 cases by vary parameters, the highest thermal efficiency was 260 mm of diameter of pot, 20 mm of distance between burner and pot and 145 mm of diameter of burner head condition and the lowest thermal efficiency was 220 mm of diameter of pot, 20 mm of distance between burner and pot and 145 mm of diameter of burner head condition. The obtained results provide useful for development of heating process by infrared burner technologies and to guide the development of effective infrared burner too lead the way in energy-saving way and reduce environmental impacts.

Keywords: Infrared Gas Stove; Temperature Distribution; Thermal Efficiency; Finite Element

1. INTRODUCTION

Data from the Energy Policy and Planning Office, Ministry of Energy, Royal Thai Government found that the usage of fuel gas in the year 2007 to 2015 is likely to increase every year [1]. In addition, the price of fuel gas in Thailand was found to have a tendency to rise every year as well [2]. However, because energy is limited, in order to reduce the energy consumption of the country should be find ways to use energy most efficiently as possible.

Infrared burner is a type of low gas pressure. The working principle of infrared burner is relying on heat transmission by radiation. Infrared (IR) is a part of the electromagnetic spectrum. IR is invisible radiant energy, electromagnetic radiation with longer wavelengths than those of visible light, extending from the nominal red edge of the visible spectrum at 700 nanometers (frequency 430 THz) to 1 mm (300 GHz). From survey the market, it is found that the infrared burner that supplied in Thailand all have the same type of radiation is the release of gas using ceramic plate [3]. The other characteristics are not as popular or widespread in the country because the producers lack knowledge and technology in production. Current infrared burner is gaining more popularity in households due to the infrared burner is a low gas pressure of no flames. The advantages of infrared burner are reducing the consumption of cooking gas stove over conventional, characterized by burning smokeless, clean applications and can be easily controlled as desired. Results in the annual sales volume of all operators in Thailand of infrared burners is 430,000 stoves per year.

Many previous researches studied on drying products using infrared radiation. The study found that drying using infrared reduces drying time less than the traditional drying (using hot air). There are some researches described the basic principles of infrared radiation and applications in the food industry such as baking, roasting and drying, the study found that the infrared can transfer heat to the food more efficiently and it can be reducing the time and cost of process [4-6]. It was also found that the products from infrared heating have better quality than conventional heating [7]. The rate of gas consumption was compared during the cooking of meat products using a gas stove with a traditional model and an infrared gas burner of ceramic plates [8]. It is observed that the infrared gas burner can help reducing gas consumption by about 55%. However, a few studies considered model of heat transport during heating by infrared burner, especially a detailed study of the effect of heating time, size of boiling pot of water, the distance between the burner and the boiling pot of water and the size of the burner on temperature distribution and thermal efficiency of the infrared burner. This is because complexity of the mathematical model of pot and infrared burner.

In this study, the influences of diameter of boiling pot of water, the distance between the burner and the boiling pot of water and the size of the burner on temperature distribution and thermal efficiency during heating using infrared burner are investigated. In order to verify the accuracy of the present model, the computer simulation results are validated with an experimental results. The test method is reference from the low-pressure gas burner in households with LPG test (TIS No. 2312-2549) and the Development of energy efficiency standards infrared burner project. An axially symmetric model of pot and infrared burner are considered in this study, which minimized the computation time while maintaining good resolution and represents the full 2-D results. The governing equations as well as initial and boundary conditions are solved using the axisymmetric finite element method (FEM).

2. RESEARCH SIGNIFICANCE

The significance of this study will be the basis for the study and analysis the effects of various parameters on temperature distribution and thermal efficiency during heating using infrared burner. The key results from this research will be useful in guiding the development of more efficient infrared gas stove. It also serves as a model for developing infrared gas stoves as well as other types of stoves to save energy and reduce environmental impact.

3. EXPERIMENTAL PROCEDURES

For experimental purposes, the test method is referenced from the low-pressure gas stove in households with LPG test (TIS No. 2312-2549) and the Development of energy efficiency standards infrared burner project [3].

Infrared gas stove is used in the experiment. The infrared gas stove is composed of ceramic plate that it emits heat to the pot. The infrared gas stove that is used in the experiment is shown in Fig. 1. In this experiment, the three sizes of aluminum pots (diameters of 220, 240 and 260 mm) as shown in Fig. 2 are used to compare the temperature and thermal efficiency.

Experimental methods to determine the thermal efficiency of the infrared gas stove in this study are in the Fig. 3 and follow by the steps. Starting with check and prepare experimental equipment, set up stove and connect the stove with gas gauge, pressure equipment, gas temperature gauge and valve gas as shown in Fig. 4. Then adjust the gas valve to the maximum gas inject position at gas pressure of 280 millimeters water (mmH_2O). Warm the burner for 5 minutes to remove stains dirt and oil. Turn off the stove and place the pot on the center of stove then put the thermometer to measure temperature.

Fig. 1 Infrared gas stove which is used in the experiment.

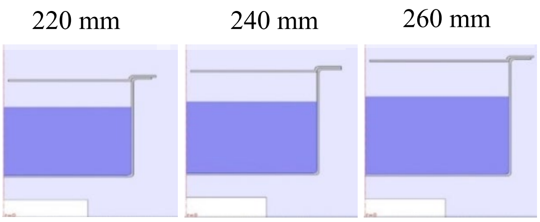

Fig. 2 Aluminum pots for experimental study.

Fig. 3 The water in the container is boiled in the experiment.

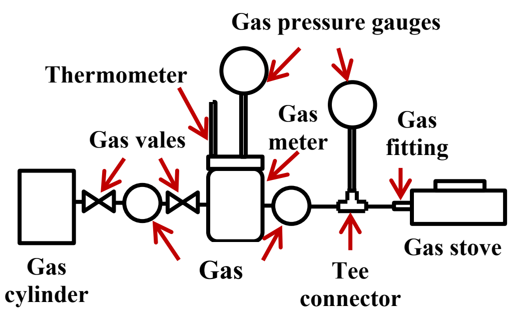

Fig. 4 Experimental apparatus.

The position for measuring the temperature of the center of the water at the height of 5 mm from the bottom of the pot is considered. Follow this procedure until the temperature of water increase from initial for 50 °C. Finally, turn off the stove; record the last temperature of water and quantity of gas. An experiment is repeated 5 times. The data of the test will be used to calculate the thermal efficiency of infrared gas stoves. Before taking the test again, pot cleaner clearly to minimize heat loss. The temperature measured in experimental is recorded by using digital thermometer during heating. The dimensions of pot and infrared gas stove and conditions in this experiment setup is used for the simulation.

4. NUMERICAL ANALYSIS

4.1 Physical Model

Analysis of heat transfer in water during heating by using infrared gas stove is presented. The system of governing equations as well as initial and boundary conditions are solved numerically using the FEM via COMSOL™ Multiphysics. In order to verify the accuracy of the present model, the computer simulation results are validated against the experimental results with the same conditions. The mathematic model used in computer simulation is divided into two parts, namely a container (pot) and infrared gas stove as shown in Fig. 5. The pot made of aluminum material. Because of the pot and burner are cylinder shape and the pot are located on the center of burner, an axially symmetric model is considered in this study for save the computation time. The axially symmetric model of pot and infrared gas stove for heat transfer analysis of water heating by using infrared gas stove is proposed. Heat absorbed by the water and converted into internal heat generation, which causes its temperature of water to rise. The convergence test is carried out to identify the suitable numbers of element required. The properties of materials are based on properties of equipment that use in experiment. There are properties of air, water and aluminum as shown in Table 1.

Table 1 The properties of materials [9-11].

Properties	Air	Water	Aluminum
Density (kg/m^3)	1.186	1000	2700
Heat capacity (J/kg·K)	1005	4186	897
Thermal conductivity (W/m·K)	0.0259	0.6065	204

4.2 Equations for Heat Transfer Analysis

The heat transfer model is developed to predict the temperature distribution in the water. The assumptions have been offered for computer analysis is as follows: lack of the combustion of gas fuel, unconsidered a container base and no phase change and no chemical reaction in the water. Also, thermal properties of air, water and aluminum pot are constant. Fig. 6 shows the internal and external boundary conditions of pot. Temperature boundary condition is to specify the temperature from the burner head. The boundary condition of heat continuity is to temperature continuity in the different domain. Thermal insulated boundary conditions are applied on the external of the air. The inlet condition is to add the velocity to the model. The condition outflow is used in the flow problem with the unknowns of flow velocity and pressure. The boundary condition of wall is specific $\vec{u} = 0$. The open boundary is used to specify at the outlet. The initial condition of water is defined as $T_0 =$ 25 °C at t = 0 s in order to comply with the experiment. The simulation measured point of water temperature at 5 mm above inside bottom of pot to find thermal efficiency.

The governing equation describing the heat transfer phenomenon is given in Eq. (1):

$$\rho c \frac{\partial T}{\partial t} + \rho c \vec{u} \cdot \nabla T = \nabla \cdot (k \nabla T) = 0 \qquad (1)$$

Where ρ is the density, c is the specific heat capacity, T is the temperature (°C), t is the time (s), $\vec{u}$ is the velocity (m/s) and k is the thermal conductivity.

Corresponding to heat transfer analysis, fluid flow analysis inside the water and air is assumed in axially symmetric model. Fluid flow analysis is formulated to describe the water and air velocity distributions. Using standard symbols, the governing equations describing the fluid flow are given as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{u} \right) = 0 \qquad (2)$$

Navier-Stokes equation:

$$\rho \frac{\partial u}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = \nabla \cdot \left[- pl + \mu \left(\vec{u} + \nabla \vec{u} \right)^T - \frac{2}{3} \mu \left(\nabla \cdot \vec{u} \right) l \right] \qquad (3)$$

Where ρ is the density (kg/m^3), t is the time (s), $\vec{u}$ is the velocity (m/s), p is the pressure (Pa), μ is the viscosity (Ns/m^2) and l is the identity matrix tensor.

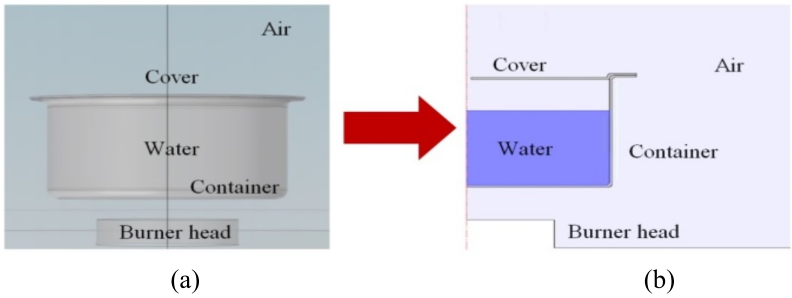

Fig. 5 The numerical model that used in the simulation (a) 3-D model and (b) 2-D axial symmetry model.

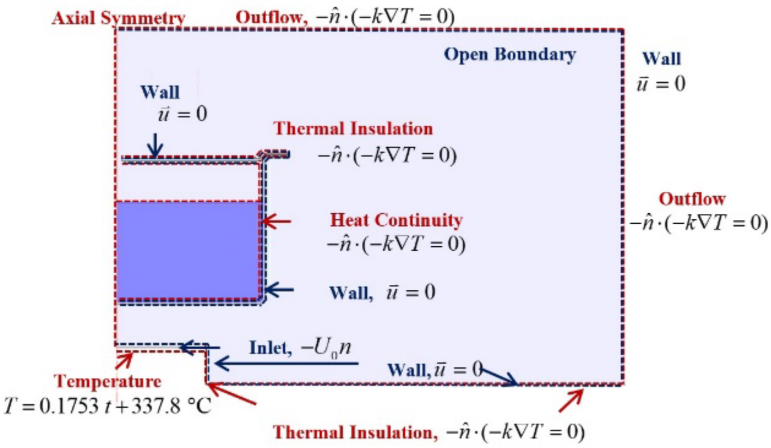

Fig. 6 Boundary conditions for numerical analysis.

The equation for calculate the thermal efficiency is given in Eq. (4) [1]:

$$\eta=\frac{m\times c\times(T_2-T_1)}{V\times Q}\times\frac{273+T_g}{298}\times\frac{101.3}{P_s+P_m-P_{sat}}\times 100\,\% \tag{4}$$

When η is the thermal efficiency (-), m is the mass (kg), c = 0.004186 MJ/kg.K is the specific heat capacity, T_1 = 25 ± 2 °C is the initial temperature of water, T_2 = 75 ± 2 °C is the final temperature of water, V is the amount of gas used test (m^3), Q = 107.86 MJ/m^3 is the lower heating value, T_g is the temperature of the gas during the test (°C), P_s is the atmospheric pressure during test (kPa), P_m is the pressure of the gas during the test (kPa), P_{sat} is the pressure of saturated stream at a temperature of gas during test (kPa).

However, because this study focuses on the study of water temperature that effects on the thermal efficiency during infrared gas stove heating, the water velocity value is not presented in this research.

5. RESULTS AND DISCUSSION

5.1 Verification of the Model

The number of elements where solution is independent of mesh density is found to be 26,754 elements. It is reasonable to confirm that, at this number of elements, the accuracy of the simulation results is independent from the number of elements through the calculation process. The water temperature during boiling the water with the infrared gas stove of the experimental study and numerical study in condition pot size 220, 240 and 260 mm, distance between burner and pot 25 mm and diameter of burner head 145 mm are shown in Table 2, Table 3 and Table 4, respectively. The water temperature of the experiment and simulation (experiment: simulation) at 720 s of 220, 240 and 260 mm of pot size are 70.1:61.095, 65.2:60.55 and 57.7:61.19, respectively. The average error between the experimental results and simulation results of water temperature with the different 220, 240 and

260 mm of diameters of pot are 10.85011%, 6.754703% and 2.13054%, respectively. The average error of the experimental result and simulation results is part of the initial water temperature. The initial temperature of the simulation is specified at 25 °C but the experimental initial temperature is 25 ± 2 °C. It is found that the results of experiment and simulation are consistent. The results also indicate that an increase in the heating times results in an increase temperature. Even though there have a little different, the both of trends is similar. Therefore, this model can use to analyze and study thermal efficiency of infrared gas stove.

Table 2 The comparison between the experimental study and simulation study of 220 mm of diameters of pot.

Time	Water temperature of the experiment (°C)	Water temperature of simulation (°C)	Error (%)
0	25.2	25.00001	0.714809
60	28.4	27.86652	1.87844
120	31.8	30.11759	5.350123
180	35.6	32.38299	8.934223
240	39.4	34.81065	11.60323
300	43.1	37.447	13.19656
360	47.1	40.27288	14.49494
420	50.9	43.29045	14.94999
480	54.4	46.53052	14.4974
540	58.5	49.92689	14.65489
600	62.4	53.52855	14.27202
660	66.3	57.24255	13.6092
720	70.1	61.09507	12.89554
		Average error (%)	10.85011

5.2 Effect of Parameters Varying

The different parameters are studied with the numerical method to compare the water temperature and thermal efficiency. The different pot sizes (220, 240 and 260 mm), distances of the burner and pot (20, 25 and 30 mm) and the diameters of burner head (135, 145 and 155 mm) are studied in 9 cases which are shown in Table 5. Changes of parameter are applied; the other parameters are constant. For example, in the first three cases, the diameters of pot are 220, 240 and 260 mm with the constant parameters of 25 mm of distance between burner and pot and 145 mm of diameter of burner head. The cases number 2, 4 and 8 are in the same conditions because there is one vary parameter with two constant parameters.

The impact of variable parameters, namely diameters of pot (220, 240 and 260 mm), distance between burner and pot (20, 25 and 30 mm) and diameters of burner (135, 145 and 155 mm) to thermal efficiency of an infrared burner are studied in this research in 9 cases as shown in Table 5.

Table 3 The comparison between the experimental study and simulation study of 240 mm of diameters of pot.

Time	Water temperature of the experiment (°C)	Water temperature of simulation (°C)	Error (%)
0	25.0	25.00001	0.0799
60	27.7	27.94727	0.892688
120	31.3	30.25616	3.334943
180	34.0	32.53411	4.311436
240	37.8	34.93435	7.532159
300	41.0	37.53286	8.45645
360	44.4	40.30004	9.23415
420	47.8	43.24168	9.574064
480	51.7	46.38212	10.25131
540	55.1	49.7054	9.856007
600	58.5	53.19229	9.073008
660	61.8	56.7887	8.138628
720	65.2	60.54902	7.076398
		Average error (%)	6.754703

Table 4 The comparison between the experimental study and simulation study of 260 mm of diameters of pot.

Time	Water temperature of the experiment (°C)	Water temperature of simulation (°C)	Error (%)
0	24.6	25.00003	1.70883
60	27.0	28.04433	3.714232
120	29.5	30.46776	3.210564
180	32.4	32.83231	1.334285
240	35.1	35.31972	0.625977
300	37.9	37.96444	0.275861
360	40.7	40.76823	0.118438
420	43.6	43.73269	0.258345
480	46.4	46.95739	1.114098
540	49.4	50.25008	1.803234
600	52.2	53.79481	3.094697
660	55.0	57.38981	4.383071
720	57.7	61.19396	6.055386
		Average error (%)	2.13054

Table 5 The thermal efficiency of infrared burner with varying parameters.

Cases	Diameters of pot size (mm)	Distances between burner and pot (mm)	Diameters of burner head (mm)	Thermal efficiency (%)
1	220	20	145	46.452
2	240	20	145	56.863
3	260	20	145	56.891
4	240	20	145	56.863
5	240	25	145	54.680
6	240	30	145	53.531
7	240	20	135	50.684
8	240	20	145	56.863
9	240	20	155	54.671

In various parameters, the other parameters are fixed. The results showed that the bigger pot size has thermal efficiency more than the small pot size. The thermal efficiency in the small gap between burner and pot is higher than the widely size. In various diameters of burner head, the middle size which is 145 mm has the thermal efficiency more than the other sizes. Fig. 7 shows the comparison of thermal efficiency by parameters varying.

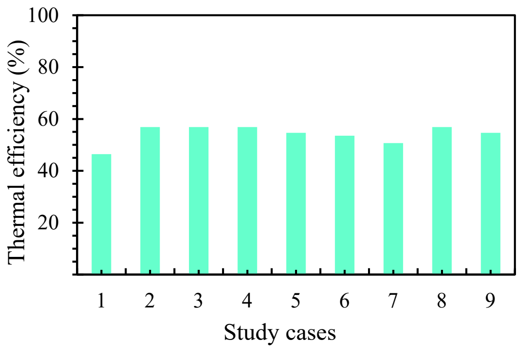

Fig. 7 Comparison of thermal efficiency by parameters varying.

The graph of thermal efficiency of parameters which are diameters of pot, distances between burner and pot and diameters of burner head is shown in Fig 7. When compared the thermal efficiency in various diameter of pot and distance between burner and pot conditions, the results of various size of pot have the difference more than the other parameters. The highest thermal efficiency of 9 cases is 260 mm of diameter of pot, 20 mm of distance between burner and pot and 145 mm of diameter of burner head at 56.891% and the minimum thermal efficiency is 220 mm of diameter of pot, 20 mm of distance between burner and pot and 145 mm of diameter of burner head condition at 46.452%.

Fig. 8 shows the temperature distribution of 9 cases studied. It can be seen that the temperature distribution of 135 mm of diameter of burner head is different from the other burner head sizes. The area of head of burner and bottom of pot make the shape of temperature distribution different from the 145 and 155 mm of diameters of burner head. The small head of burner results in less area for heat transfer than the huge diameters of burner head, and the distribution of water temperature is consistent with heat transfer. Water temperature of 135 mm of diameter of burner head is less than water temperature of 145 mm and 155 mm, respectively. In addition, the water temperature of small gap between burner and pot is more than water temperature of the huge distances between burner and pot. The huge distances between burner and pot have longer distance to transfer the heat than the small distance and have an opportunity for heat loss to surrounding more than little distance.

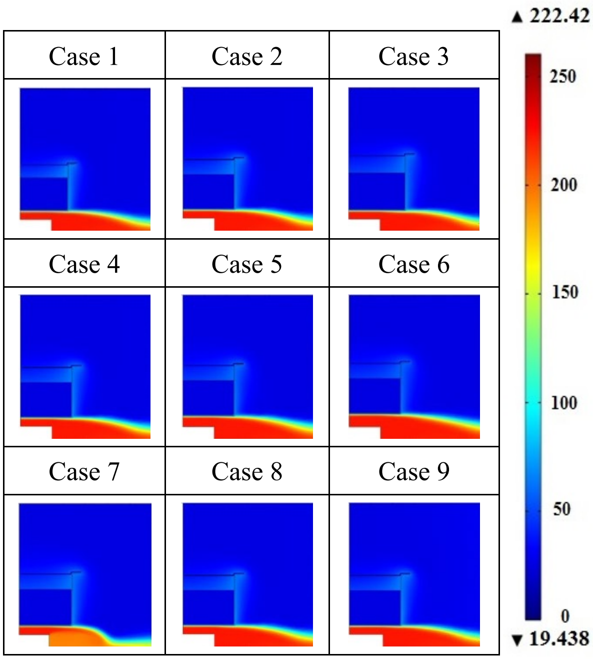

Fig. 8 Comparison of water temperature of experiment and simulation by parameters varying.

6. CONCLUSIONS

Thermal efficiency of infrared burner in varying of parameters which are diameters of pot (220, 240 and 260 mm), distances between burner (20, 25 and 30 mm) and pot and diameter of burner head (135, 145 and 155 mm) are studied in this research. The simulation results and are compared with the experimental results. The results showed that the presented model associated with assumptions, and initial and boundary conditions can predict the temperature rise during infrared gas stove heating. The conclusions of this study can be summarized thus:

1) This numerical model can solve the results of the heating of water by infrared gas stove. The average error of water temperature between simulation results and experimental results in 220, 240 and 260 mm of diameter of pot are 10.85011%, 6.754703% and 2.1305%, respectively.

2) The parameters are effect to the water temperature and thermal efficiency. In 9 cases by varying of the parameters, the simulation results show that the diameters of pot size had the greatest effect on the change in thermal efficiency.

3) The 260 mm of diameter of pot, 20 mm of distance between burner and pot and 145 mm of diameter of burner head has the maximum thermal efficiency and the 220 mm of diameter of pot, 20 mm of distance between burner and pot and 145 mm of diameter of burner head condition has the minimum thermal efficiency.

The complete mathematical model is useful for the development of heating process by infrared burner technologies and is a way to increase the thermal efficiency of various devices.

7. ACKNOWLEDGMENTS

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