Energy xxx (2014) 1–6

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Numerical and experimental methodology to measure the thermal efficiency of pots on electrical stoves

Francisco J. Cadavid, Yonatan Cadavid*, Andrés A. Amell, Andrés E. Arrieta, Juan D. Echavarría

Grupo de Ciencia y Tecnología del Gas y Uso Racional de la Energía, Facultad de Ingeniería, Universidad de Antioquia, Calle 67 N° 53 − 108, Bloque 19 − 000, Medellín, Colombia

ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form
8 May 2014
Accepted 6 June 2014
Available online xxx

Keywords:
Numerical simulation
Pot
Electrical stove
Thermal efficiency

ABSTRACT

In this paper, we present a methodology for calculating the thermal efficiency of a pot on an electric stove using numerical simulations in ANSYS FLUENT®. The system domain was divided into three subsystems: electrical resistors, the air volume inside the resistors, and the pot. It was determined that the heat transfer to the pot was mainly caused by conduction between the heating element and the pot surface, representing 85.7% of the total energy going into the system. Heat transfer by convection and radiation represented 13% and 1.3% of the total incoming energy, respectively. A method to set the initial value of the contact resistance between the electrical resistance and the pot based on experimental tests is also presented. This initial contact resistance value is a key parameter for the correct simulation of the system. The numerical simulations and experimental tests corresponded well with one another, with a difference of no more than 15% for all geometries analyzed. Finally, a substantial stove improvement is proposed. The enhancement consists of the suppression of the circulating currents that are formed inside the stove by adding an insulating material. With this improvement, the heat losses to the surroundings were reduced from 15.19% to 6.64%. And therefore, a potential reduction of the cost of living is possible in the main urban centers of Colombia.

1. Introduction

Pots and utensils used for cooking and food preparation typically work on natural gas, coal, biomass, or electric stoves. Natural gas is the most used energy source. However, the coverage of residential natural gas networks in major urban centers and rural areas in Colombia was 71.3% and 57.3% in 2012, respectively, and the national electricity network coverage for residential use was 97.6% [1]. As a result the use of electricity as a heat source for cooking food is approximately 9% in the main urban centers of Colombia, reaching a maximum peak of 21% in the region of Antioquia and 12% in the second largest city of Colombia [1,2]. This phenomenon is more evident in low-income populations.

In Colombia, up to 72.6% of the electricity generated is supplied by hydroelectric stations [3]. However, the cost of electricity for residential use is high compared to the cost in other South American countries. In 2008, Colombia was ranked fourth with a price of 135 USD/MWh, below only Chile, Brazil, and Uruguay [4]. Thus, it is necessary to find ways to improve the thermal efficiency of residential cooking systems because the cost of electricity affects the economy of a significant segment of Columbia's urban population [5].

Several studies about energy efficiency in cooking pots have focused primarily on the stove type and the type of fuel used. Agenbroad et al. [6,7] studied the combustion efficiency of stoves using biomass as a fuel in rural areas without access to an electrical interconnection system or natural gas network. They created a baseline for calculating greenhouse gas emissions, particulate matter emissions, and combustion efficiency and proposed an efficient operating range according to the power and dimensionless criteria. Natarajan et al. [8] studied vegetable oils used as fuel instead of wood in cooking stoves. They reported increases in efficiency by up to 14%. However, to date, no studies have attempted to improve cooking efficiency in urban or rural areas with access to an electrical grid but with low-income and poor social conditions.

Several studies have been carried out to determine the performance of cooking pots and natural gas used as fuel. Hannani et al. [9] highlighted the influence of pot diameter, height, material thermal conductivity, and wall inclination on the thermal

* Corresponding author. Tel.: +57 4 219 8098; fax: +57 4 211 9028.
E-mail addresses: yonatan.cadavid@udea.edu.co, yonatan.cadavids@gmail.com (Y. Cadavid).

http://dx.doi.org/10.1016/j.energy.2014.06.017
0360-5442/

performance. Gaur et al. [10] proposed a pot with a concave top, which was shown to reduce cooking time by 10–13% compared with traditional pots. Narasimha Rao and Subramanyam [11] proposed a cooking vessel with a central annular cavity that increases the effective area of heat transfer in the vessel and reduces cooking time.

Kerr [12] found that a wide-diameter pot is heated more efficiently than a small-diameter pot. Furthermore, a thin wall is more beneficial because of the lower heat transfer resistance and shorter time in which food is heated. When the heat source is mainly thermal radiation, the pot walls must be coated with a dark color to avoid reflection.

The purpose of this paper is to present a methodology to simulate and evaluate the heat transfer and overall thermal efficiency of a pot by electrical resistance heating. We evaluate the effect of geometry on the heat transfer to the load through numerical simulations in ANSYS-FLUENT®. Furthermore, the dominant heat transfer mechanism is established. The numerical results are compared with experimental measurements to set the prediction level of the model used. The simulation methodology allows for the design of more efficient cooking pots and thus reduced cooking time.

2. Numerical simulation

The simulation process considered the different diameters and heights of pots that are commercially available in Colombia; specifically, this study considered diameters of 16 and 24 cm and heights of 5, 10, and 15 cm. The heat source simulated is a commercial electrical stove of three electrical resistor spirals with an 8-mm-wide, 6-mm-high rectangular cross section and a 3.5-mm-wide contact surface. The net power heating is 1.0 kW. The load (the mass to be heated) simulated is boiling water in a location 1530 m above sea level. Table 1 lists the geometrical characteristics of the pots.

2.1. Calculation model

Fig. 2 presents the overall heat transfer diagram, which is driven by the following three modes of heat transfer: heat conduction between the electrical resistors' surface and the pot's bottom surface, convection between the hot air inside the reflector shield and the pot's surfaces (Q_{c2}), and thermal radiation from the reflector shield and the pot's surfaces (Q_{re}). Similarly, the heat generated inside the electrical resistance is transferred by conduction, convection (Q_{c1}), and radiation (Q_{rr}) to the surroundings. The simulation was carried out in steady-state conditions using a cylindrical coordinate system. The system domain is divided into the following three subsystems for better phenomena understanding: electrical resistors, the air volume inside the resistors, and the pot. These three subsystems are integrated into a single domain in ANSYS FLUENT to be solved with the boundary conditions (see Fig. 3).

2.1.1. Electrical resistor subsystem

This subsystem consists of three concentric rings with a heat source term equivalent to the nominal stove heating power (1000 W). This subsystem is modeled by Eq (1).

Table 1
Geometrical dimensions of the simulated pot.

Number	A (mm)[a]	B (mm)[a]	Thickness (mm)	Water volume (lt)	Material
1	160	123	1.4	1.063	Aluminum
2	240	43	1.4	0.961	Aluminum
3	240	103	1.4	2.5	Aluminum

[a] Fig. 1 presents the dimensions A and B.

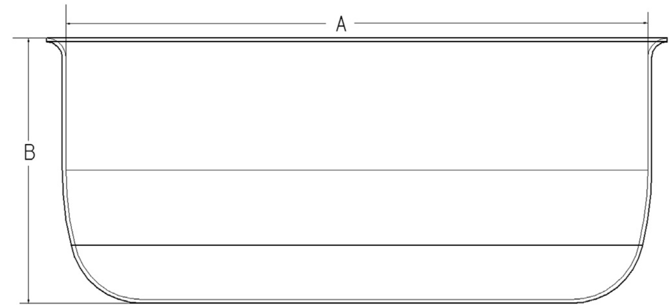

Fig. 1. Overall pot dimensions.

$$\nabla.(k\nabla T) + \frac{I^2}{R} = 0 \quad (1)$$

where I is the current passing through the resistance in amperes and R is the resistance value in ohms. The contact resistance between the electric heater's surface and the pot is considered by assuming an additional wall thickness on the electric resistor surface. This topic is described in the user manual of ANSYS FLUENT ® by Eq (2) [13].

$$R_c = \frac{\Delta z}{k_e} \quad (2)$$

where k_e is the average thermal conductivity of the two materials.

2.1.2. Air volume inside the resistor subsystem

The air volume is modeled by solving the equations of conservation of mass, momentum, and energy in a laminar regime and considering buoyancy effects [14]. The radiation model uses discrete ordinates; the angular discretization has four divisions in the polar angle and four divisions in the azimuth. The hemispherical sector is divided into four pixels in the polar direction and four pixels in the azimuthal direction [13]. The subsystem heat input originates from thermal radiation and convection emitted by the electrical resistors. The boundary conditions for this subsystem are placed in the reflector shield that reflects the radiation from the electrical resistances and isolates the hot air volume from the surroundings. Therefore, there is a heat loss by convection, Q_{c3}, and radiation, Q_{r1}, with the surroundings. The coefficients used were 10 W/m^2 K for convection and an emissivity of one for thermal radiation at a temperature of T_{se}.

2.1.3. Pot subsystem

This subsystem is modeled by Eq (1) without the thermal generation source term. The subsystem heat input originates from the electrical resistors, radiation reflected, and internal air convection. The boundary condition is the convection on the surface in contact with water; the fluid temperature is (T_b) 96 °C (boiling point of water). The convection coefficient is calculated from Eq (3), where the parameters are obtained from the experimental test described in the section three. The convection coefficient calculated is 130 W/m^2 K. The water mass variation along the process is not considered for this subsystem.

$$h = \frac{h_{fg}\Delta m}{A(T_s - T_{eb})} \quad (3)$$

where h_{fg} is the enthalpy of vaporization of water (2300 kJ/kg), Δm is the mass of water evaporated in the process, A is the contact

Please cite this article in press as: Cadavid FJ, et al., Numerical and experimental methodology to measure the thermal efficiency of pots on electrical stoves, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.06.017