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Experimental and Numerical Investigation of Two Different Traditional Hand-Baking Flatbread Bakery Units in Kashan, Iran

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ABSTRACT

In present study, experimental measurements and mathematical modeling were employed to investigate the different parameters, such as temperature of different parts of oven, natural gas consumption, flue gases temperature and portion of different heat transfer mechanisms during baking, in two different traditional flatbread bakeries called Sangak (/săngăk/) and Barbari (/bărbări/). In all studied ovens, the bread receives the energy from natural and forced convections, conduction, and radiation (volumetric and surface radiation). The main aim of this study is introduction of a numerical simulation in order to investigate and validate the flatbread bakery ovens. This validation has resulted in to analyze different bakery ovens using numerical methods and consequently reduce the experiments costs. Due to fulfill this demand two numerical models are used and solved using control volume method based on SIMPLE algorithm and RNG k-ε method. The obtained results showed that numerical solution can make a reliable result in case of modeling bakery ovens, because of a good agreement between numerical and experimental results with the maximum error of 12.57%.

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1. INTRODUCTION

Bread in its numerous forms is one of the most main foods consumed by humanity. Bread as a dominant food of Iranian people has the great role in nutrition, industry and economy of the country [1]. According to Figure 1, the various types of Iranian traditional hand–baking breads that are baked in Kashan (/käʃän/) are Sangak (/săngăk/) and Barbari (/bărbări/). In general the traditional bakeries are categorized into two *hand–baking* and *machinery* groups based on their ovens. There are about 70,000 bakeries in Iran that 35% of them bake hand–baking traditional flatbread. Therefore, studying the hand–baking of the traditional flatbreads is by far more important compared with the French and industrial breads in Iran. Figure 1 also elucidates schematic representations of different types of traditional flatbreads hand-baking units are studied in present work. The comparison of the energy intensity index between Iran and most countries in the world reveals the inappropriate conditions of energy consumption in Iran. Hence, based on the foregoing fact that the bread is one of the most important food products, introducing a solution to reduce energy consumption of baking bread can improve the energy intensity in Iran [2]. Furthermore, one of the valuable energy resources in Iran is natural gas that has a growing consumption in all parts. According to the reports, the highest natural gas consumption in Iran is related to commercial, house, power plants, and industrials consumptions. Besides, one of the important commercial parts that have not received considerable attention is the bread baking industry, and as far as most of the bakeries in Iran consume natural gas, these units of baking bread have high effects on natural gas consumption.

Mondal and Datta [3] studied the dough bread baking both experimentally and numerically. By drawing the temperature distribution diagram and the bread humidity, and comparing them with the experimental results, good agreements among the results can be observed. Moreover

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for French Baguette bread, the portion of conduction heat transfer was 19% and convective heat transfer was 14% [4]. Ovalle et al. [5] in their work represented a pilot scale convective oven as a nominal scenario, and provided empirical data for temperature. Their approach consisted of three–dimensional (3D) computational fluid dynamic (CFD) simulations at various temperatures and geometrical variants of the internal baffle plate. Their obtained results proved that the baffle plate configuration applied an important hydrodynamic effect in the reduction of the pre-heating time. Hicks et al. [6] studied the local shear flow behavior of bread dough with usage of CFD. According to their results shearing has an important role in the point of the gluten network within bread-dough.

Hashemi et al. [7] studied the energy and exergy analysis and investigated the solutions for reducing fuel consumption in the *hand-baking* bakeries of Iranian traditional flatbreads. The results revealed that by controlling the excess air, the optimum insulation of furnace and recovering the heat losses from the chimney, it is possible to increase the energy and exergy efficiency for breads. Hashemi et al. [8] by experimental measurements and mathematical equations, reported portions of different mechanisms of heat transfer during the baking process of Taftun *hand-baking* flatbreads. The results of thermal diffusivity and emissivity optimization illustrated that fuel consumption for Taftun bakeries can be reduced about 8%. Due to important applications of numerical modeling in analysis of different furnaces such as bakery ovens, this subject has been studied by a large number of researchers [1-14]. As it can be seen, neither experimental nor numerical analysis has been done over the investigation on the validation of hand–baking Iranian traditional flatbread ovens using computational fluid dynamics (CFD) method. There are two common approach to investigate furnaces: experimental measurements and numerical simulation. It is clear that use of numerical simulation is more cost effective and inexpensive in money spending and computational time than experimental measurements. The authors of this study would like to continue and complete their previous studies [7, 8] and they would like to introduce validated numerical models to investigate bakery ovens instead of using empirical methods. In order to fulfill this demand they investigate two different Sangak and Barbari ovens in Kashan and try to design and simulate these ovens. Furthermore, for designing and simulating ovens they consider logical simple assumptions, applye thermophysical and radiative properties of the studied ovens and analyze heat transfer and fluid flow inside ovens. In fact, since the computation costs of numerical simulation is less than analytical methods the main important aim of this study is to achieve a validated CFD model to investigate flatbread bakery ovens. If results of numerical and experimental methods are in remarkable coincidence, CFD simulation of bakeries will be a reliable and cheap method for future investigations. Therefore, other investigators can use these models and study different effects on baking flatbread ovens to optimize them instead of performing expensive and time-consuming experiments.

2. MATERIAL AND METHODS

The Kashan city with 51° longitude and 30 minutes in east direction and 34° latitude and 5 minute in north direction is located in Isfahan province in Iran. All three studied bakeries in present study were located in this city. Also the properties of oven walls (material, thickness and surface area) are listed in Table 1. As it is clear in Figure 1 the measurement devices include infrared thermometer, gas analyser and flow meter. For measuring different parts of the furnace, the Infrared video thermometer, *ST–9861*, is used. This thermometer is equipped with the digital monitor and measures the temperature in the range of –30°C to 2000°C. Furthermore, this device can save the pictures and thermal properties and recorded data saved in computers. In addition, for measuring the combustion efficiency (the remained heat inside the furnace) and hot gases analysis inside the furnace the *TESTO 350 M/XL* gas analyser was used. This device can measure the concentration of nitrogen oxides (NO_x) and carbon monoxide (CO) up to 3000 ppm and 1000 ppm, respectively. Moreover the existing thermocouple inside the device can bear the temperature up to 1200°C.

The measurement accuracy of this device for NO_x for concentrations less than the 100 ppm is 5 ppm and this accuracy for CO in concentrations less than 100 ppm, was 10 ppm.

In all ovens, the bread receives the energy from convection, conduction, and radiation.

The hot gases velocities inside the furnace were determined by Equation (1) that is used for the estimation of hot gases velocities inside the oven [20, 21].

$$u_{fl}^{m} = \frac{\dot{m}_F \cdot \left(1 + A/F\right)_{mass}}{\rho_{fl} \cdot A_{fl}} \tag{1}$$

TABLE 1. Properties of ovens studied in this work

Properties of bakery		Sangak	Barbari
Side walls	Material	Fire Brick and Cement	
	Thick., Δ(m)	0.35	0.32
	Area, A (m^2)	11	3.5
Roof	Material	Fire Brick and Sand	
	Thick., Δ(m)	0.33	0.29
	Area, A (m^2)	11.8	3.7

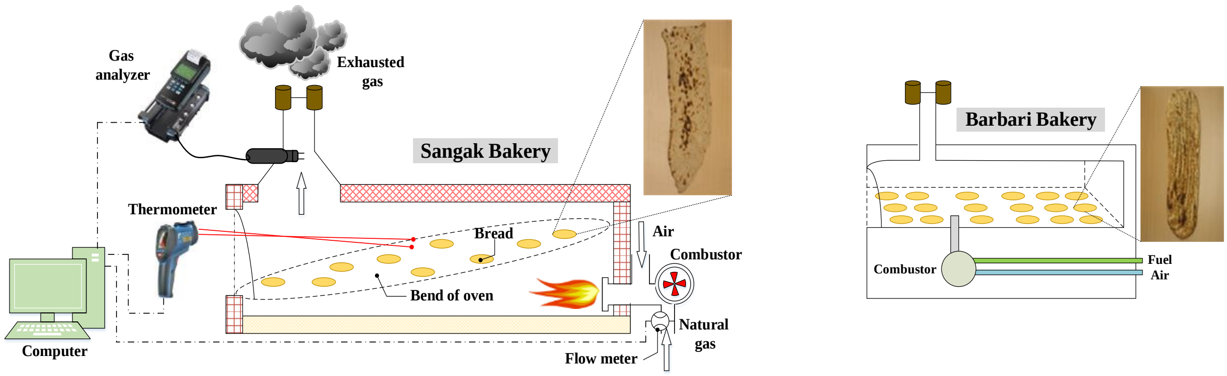


Figure 1. Schematic representation of combustion installation of bakeries and images of various types of different breads in Iranian traditional flatbread hand–baking units: Sangak and Barbari

where, $\dot{m}_F$ is the mas flow rate of natural gas, ρ_{fl} is the density of combustion products in the average temperature of the oven, A_{fl} is the specific surface of hot gases passage inside the furnace, and $(A/F)_{mass}$ is the mass ratio of air to fuel [20, 21]. The convection heat transfer rate parallel to the flat plate with length of L, to the surface unit of bread is calculated by Equation (2) [15-17].

$$\dot{q}_{conv,f} = 0.037\,\mathrm{Pr}^{0.33}\left(\frac{\rho_{fl}\cdot u_{fl}^{m}\cdot L}{\mu_{fl}}\right)^{0.8}\frac{k_{fl}}{L}(T_{ov}^{m}-T_B) \quad (2)$$

where k_{fl}, μ_{fl} and Pr are heat transfer coefficient, dynamic viscosity and Prandtl number of combustion products at the film temperature (T_{film}) of the furnace. The film temperature, we mean the average temperature of bread surface that is being baked (100°C) and average temperature of oven (T^{m}_{av}). Unlike the forced convection equations that are the same for all kinds of bread, the natural convection equations are different for horizontal flat plate (Barbari) and inclined flat plate (Sangak). Nevertheless, the hot gases flows inside the furnace flow on the cold surface (bread) for all kinds of bread [23]. For Barbari bread that is being baked, the natural convective heat transfer occurs on the cold horizontal flat plate. It is considered that the entire plate is subjected to heat and then gets hot. Because of the Buoyancy force flows toward the surface plate mostly, for high Rayleigh numbers the dominant regime is laminar. The average Nusselt number by considering the thin boundary layer estimation and the average Nusselt number value for laminar flow in the range of $10^3<\mathrm{Ra}<10^9$ are computed by Equations (3) and (4). For Sangak bread that is being baked, the natural convective heat transfer occurs on the inclined plate. For calculations related to the natural convection on the inclined plate with angle of θ to the horizon, the Nusselt number is computed by Equations (3) and (4) first. But the difference is that in the term g·sin(ζ) should be used instead of g for computing Rayleigh number (ζ=180–θ). After that using Equations (3) and (4) for the flow on horizontal flat plate, the same measurements are applied for Nusselt number. But the difference is that the term g·{0, –cos(ζ)}$_{\max}$ is used instead of using g, for measuring Rayleigh number. Then the maximum Nusselt number is chosen between these two calculated amounts, and it is used for natural convective heat transfer for the flow on the inclined surface [15, 17].

$$Nu^{T} = 0.527Ra^{1/5}\left[1+\left(1.9\,\mathrm{Pr}^{-1}\right)^{0.9}\right]^{-2/9} \quad (3)$$

$$Nu_{l} = Nu_{n} = 2.5\left(\ln\left(1+\frac{2.5}{Nu^{T}}\right)\right)^{-1} \quad (4)$$

The specific length of bread (L_B) is different based on the conditions for flat plate placement. For inclined plate (Sangak bread), the specific length equals to bread length (L), and for horizontal flat plate (Barbari bread), the specific length equals to the ratio of the bread area to the perimeter [17]. The heat transfer rate ratio to the bread by natural convection per the unit surface of the bread is calculated by Equation (5):

$$\dot{q}_{conv,n} = \frac{Nu_{n}\cdot k_{fl}}{L_B}\cdot(T_{ov}^{m}-T_B) \quad (5)$$

For measurements related to the conductivity of furnace floor, the conductive heat transfer coefficient of furnace floor should be computed. The furnace floor material for Barbari bakery is fire brick and clay, respectively. The furnace floor for Sangak bakeries consists of porous media that includes stones and hot gases. In order to solve the thermal conductivity of the bread that is being baked, the furnace floor is considered as the semi-infinite plate. However, in the reality the floor thickness is finite and it is not infinite; because the floor mass is higher than bread mass, this consideration for heat transfer between bread and floor is logical.

Based on the average temperature of furnace floor, it is considered that by placing the bread inside the furnace, at first a thermal increase is formed from the pastry temperature to the furnace floor temperature and then the heat transfer occurs at constant temperature of 100°C. The heat flux generated from the transferred thermal conductivity to bread that is being baked is calculated by Equation (6) [18]. In this correlation, t is the average time of baking and k_s, ρ_s and $c_{p,s}$ are thermal conductivity coefficient, density and specific heat capacity of the furnace floor, in the average furnace floor temperature (T^m_s), respectively.

$$\dot{q}_{cond,B} = k_s^{1/2}(T_s^m - T_B)\left(\frac{\pi t}{\rho_s c_{p,s}}\right)^{-1/2} \quad (6)$$

The radiative heat transfer inside the oven includes volumetric and superficial radiation. These coefficients are obtained based on average temperature of sidewalls (T^m_r) and the surface temperature of bread (T_B). It is considered that all gases inside the furnace are ideal gas mixture and the bread surface and sidewalls are grey body. It is also considered that the share of radiative heat transfer for oxygen and nitrogen gases were negligible and the diffusive radiation was ignored [17]. Therefore, the partial pressure of hot gases inside the furnace is calculated by Equation (7). Also the effective emissivity of hot gases is computed using Equation (8).

$$P_c = x_{CO_2} \cdot P, \qquad P_2 = x_{H_2O} \cdot P \quad (7)$$

$$\varepsilon_g = C_c \cdot \varepsilon_{c,1atm} + C_w \cdot \varepsilon_{w,1atm} - \Delta\varepsilon \quad (8)$$

In Equation (8), ε_c and ε_w are the emissivity of carbon dioxide (CO_2) and water vapor (H_2O) in the pressure of 1 atm and the $\Delta\varepsilon$ is the correction term of emissivity that are functions of partial pressure, average beam length (L_R), and the average temperature of hot gases that are introduced in diagrams reported in literature [17]. The C_c and C_w are the correction coefficients of pressure. They are equal to 1, because the pressure inside the furnace is 1 atm. In addition, the absorption coefficient of hot gases inside the furnace based on the emissivity of these gases for radiative heat transfer of hot gases with bread surface is computed by Equation (9) [17].

$$\alpha_g = C_c\left(\frac{T_g}{T_B}\right)^{0.65}\varepsilon_{c,1atm} + C_w\left(\frac{T_g}{T_B}\right)^{0.65}\varepsilon_{w,1atm} - \Delta\alpha \quad (9)$$

The transferred radiative heat flux from the hot gases generated from the combustion to the bread surface is computed by Equation (10). In this correlation, σ is Stefan–Boltzmann constant which is equals to $5.67 \cdot 10^{-8}$ $W \cdot m^{-2} \cdot K^{-4}$ [17].

$$\dot{q}_{r-B,V} = \sigma\left(\frac{\varepsilon_s + 1}{2}\right)\cdot\left(\varepsilon_g T_g^4 - \alpha_g T_B^4\right) \quad (10)$$

In addition to volumetric radiation, the thermal radiation of surface to surface is transferred to the bread through the walls and furnace roof. Basically, the superficial radiation related to Sangak and Barbari bakeries, the major part of radiation is emitted from the roof (with average temperature of T_m) ; that is due to bread which is not have any view on the side surfaces and it is possible to consider their view factor, zero comparing to roof view factor. The superficial radiation from the sidewalls toward the bread is being baked is neglected compared to the superficial radiation of the roof. The superficial radiative heat flux transferred from the room to one loaf of Sangak or Barbari bread is calculated using Equation (11) [17].

$$\dot{q}_{r-B,S} = \varepsilon_r \sigma\left(\left(T_r^m\right)^4 - T_B^4\right) \quad (11)$$

Therefore, the overall heat flux in the process of baking that is the sum of conductive, convective, and radiative heat fluxes is calculated by Equation (12) [17].

$$\dot{q}_{total,B} = \underbrace{\dot{q}_{conv,f} + \dot{q}_{conv,n}}_{\dot{q}_{conv,B}} + \dot{q}_{cond,B} + \underbrace{\dot{q}_{r-B,V} + \dot{q}_{r-B,S}}_{\dot{q}_{rad,B}} \quad (12)$$

3. NUMERICAL MODELLING

Based on the numerous complications of ovens for baking traditional Iranian bread, and also the problems for modeling as well as expenses, it is clear that the simplifying assumptions should be used. However, the most important point is that these assumptions should be logical and close to the reality. In this work, the system is described with the following assumptions:

1. By placing the dough on the oven floor, suddenly the temperature increase and the temperature of rotating surfaces reached to 100°C and after that the heat transfer to the bread happens at constant temperature of 100°C. At this condition, all of the existing water inside the dough evaporates. Hence it is feasible to model specific parts from oven floor in the case of maximum furnace capacity and dough were at 100°C. It should be noted that 10% safety factor is considered for measuring the share of heat for browning the bread. Thus the heat transfer to the bread becomes steady.
2. The specific numbers of dough can be placed in the oven and this number is the maximum permitted capacity of oven.

Since dimensions of the numerical models affect the performance of simulation, configurations of simulated Sangak and Barbari ovens are shown in Figure 2. This figure illustrates dimensions of the numerical models and Table 2 reports values of defined parameters.

The system is described with the following assumptions:

1. Single-phase model in an incompressible fluid is used.
2. Multi-species model of mixture of air and combustion products is used.

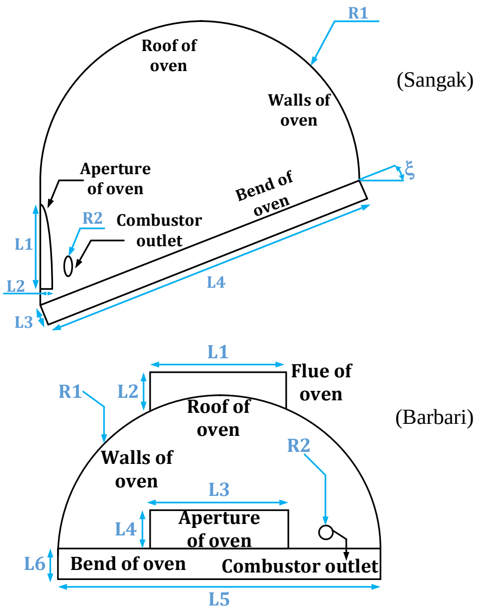


Figure 2. Configurations of simulated Sangak and Barbari ovens

TABLE 2. Properties of Figure 2

Sangak		Barbari	
Parameter	**Value**	**Parameter**	**Value**
L1	95 cm	L1	45 cm
L2	35 cm	L2	20 cm
L3	60 cm	L3	95 cm
L4	606 cm	L4	45 cm
R1	300 cm	L5	400 cm
R2	10 cm	L6	40 cm
ξ	8°	R1	200 cm
		R2	10 cm
		Depth	600 cm

3. The density of the fluid follows in the ideal gas model.
4. The fluid moves in all directions.
5. There are both turbulence and buoyancy phenomena.
6. The RNG k-ε model is used for considering turbulence effects.
7. Control volume method with SIMPLE algorithm is used.
8. The convergence criterion is 10^{-7} for all parameters. Due to intense gradients near the bread, combustor, walls and apertures, choosing the grid is highly important. In the present study, the non-uniform grid was used. Figure 3 illustrates the grid layouts used in the present work. The airflow in the bakery oven is assumed incompressible, and the governing equations describing the fluid flow are conservation equations of mass and momentum. In addition, Table 3 reports boundary conditions of numerical models. FLUENT commercial software usually solves the governing equations using Cartesian 3D coordinates and velocity components. Equation (13) is the simplified form of the mass conservation equation and is valid for incompressible flows [9, 19-26].

$$\frac{\partial \rho u_i}{\partial x_i} = 0 \tag{13}$$

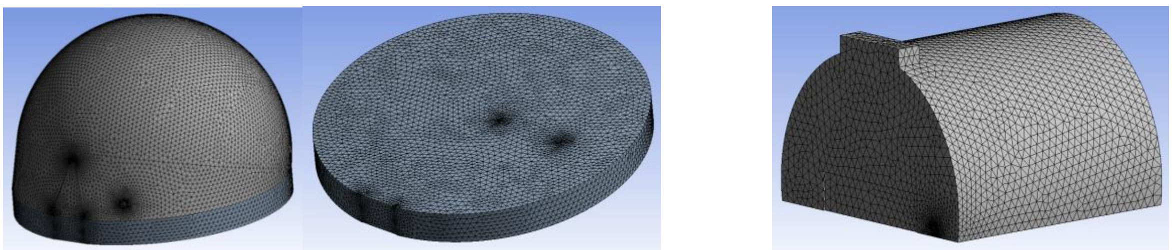
Conservation of momentum in ith–direction in an inertial (non-accelerating) reference frame is defined by Equation (14).

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i \tag{14}$$

where, P is the static pressure, τ_{ij} is the viscous stress tensor, g_i, is the gravitational acceleration and F_i is external body force in the ith–direction. The energy equation is also solved and can be written as Equation (15).

$$\frac{\partial}{\partial t}(\rho c_p T) + \frac{\partial}{\partial x_i}(\rho u_i c_p T) = \frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_i}\right) + S_h \tag{15}$$

where, c_p, T and λ are the specific heat capacity, temperature and thermal conductivity of the air, respectively. Energy source due to radiation are included in the energy source term S_h. The radiative heat transfer occurs in the oven chamber. The bakery oven filled with heated atmospheric air and combustion products was computationally complex when using this type of geometry and the thermal radiation requires application of specific radiation model.



(a) (b)

Figure 3. Grid layouts used in the present work for: (a) Sangak, and (b) Barbari bakeries

TABLE 3. Boundary conditions of numerical models

Section/Part	Boundary condition
Aperture of oven	Pressure inlet of ambient air
Combustor outlet	Velocity inlet of combustion products*
Walls of oven	Constant temperature**
Roof of oven	Constant temperature**
Bend of oven	Constant temperature**
Flue of oven	Pressure outlet
Bread	Constant temperature***

* These values are obtained by flow meter

** These values are obtained by infrared video thermometer IR–ST–9861

***The simulated bread is assumed at temperature of 100°C

As reported by Smolka et al. [20], the discrete ordinates (DO) model was selected from a large number of radiation models that are available in the ANSYS Fluent commercial software.

The terms $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$ and α_s are the model parameters [19], with the following given values $C_{1\varepsilon}$=1.42, $C_{2\varepsilon}$=1.68, Swirl factor, α_s=0.07 and $C_{3\varepsilon}=\tanh|u_2/u_3|$ where u_2 is component of the flow velocity parallel to the gravitational vector and u_3 is the component of the flow perpendicular to the gravitational vector [27].

4. RESULTS AND DISCUSSION

Due to consider grid independence test a non-uniform structured grid is used for each oven. By comparing all used mesh arrangements, in terms of *FA* and $T^m{}_r$, the grid sizes of 3,248,885 and 4,791313 nodes has been chosen to get an acceptable compromise between the computational time and the result accuracy for Sangak and Barbari ovens, respectively (see Tables 4 and 5).

In the present study, the temperature of different parts of the oven for Sangak and Barbari bakeries was measured carefully by contactless infrared thermometer device for several times. Then, an average temperature is introduced for each of internal and external walls. Figure 4 shows some results of the temperature measurements for internal walls of these ovens. The experimental results regarding analysis of the hot exhaust gases from the flue and oven combustion efficiency of the studied bakeries is presented in Table 6.

It is worth mentioning that the adiabatic temperature of the combustion in this table is obtained with GASEQ software. As can be concluded from Table 6, the combustion efficiency of the oven for the Sangak and Barbari bakeries were 68.76 and 67.40%, respectively. It means that for example in Barbari bakery, about 67.4% of fuel energy loses are from the flue gases of the oven, and the remaining energy bakes breads and loses from the walls of the oven. The average results of experiments for characteristics of studied bakeries, natural gas consumption, physical properties of breads, and the average of experimental and analytical results of the properties of different breads and mean temperature of internal walls of oven are indicated in Table 7.

The main aim of this study is to introduce a numerical simulation in order to validate and investigate flatbread bakery ovens.

TABLE 4. Grid independence test in term of *FT* and $T^m{}_r$ for Sangak oven

	Nodes	*FT*	Error *FT*	$T^m{}_r$	Error $T^m{}_r$
1	976,319	187.89	53.10%	234.59	48.34%
2	2,464,985	287.66	26.58%	347.99	20.50%
3	3,248,885	364.13	1.02%	419.32	3.23%
4	3,517,753	367.84	–	432.87	–

TABLE 5. Grid independence test in term of *FT* and $T^m{}_r$ for Barbari oven

	Nodes	*FT*	Error *FT*	$T^m{}_r$	Error $T^m{}_r$
1	2,872,981	130.52	52.45%	245.11	62.30%
2	4,321,919	198.98	32.27%	397.81	11.31%
3	4,791,313	263.19	4.65%	442.82	1.94%
4	4,874,721	275.43	–	451.43	–

Figure 4. Temperature measurements with IR thermometer for different parts of ovens: (a) Sangak, and (b) Barbari

TABLE 6. Analysis of flue gases and combustion efficiency for different bakeries with TESTO gas analyzer

Bakery	O_2 (%)	CO_2 (%)	CO (ppm)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)	T_{ad} (°C)	AT (°C)	FT (°C)	e_x (%)	η_{comb} (%)
Sangak	13.52	4.24	270	26	0.6	26	966.75	19.90	341.3	162	68.76
Barbari	15.81	2.94	385	3	1.3	5	715.05	16.90	256.2	273	67.40

TABLE 7. Experimental results about features of different breads

Bakery	V_F ($m^3.hr^{-1}$)	m_d (kg)	m_B (kg)	Δt (s)	n_B–	L_B (m)	A_B (m^2)	T^m_{ov} (°C)	T^m_s (°C)	T^m_r (°C)	T_g (K)
Sangak	6.01	0.60	0.45	1200	29	0.63	0.17	390	365	400	614.45
Barbari	8.28	0.63	0.44	720	24	0.09	0.15	370	285	410	529.35

This validation can make a new approach to analyze different bakery ovens using numerical methods and consequently reduce the experiments costs.

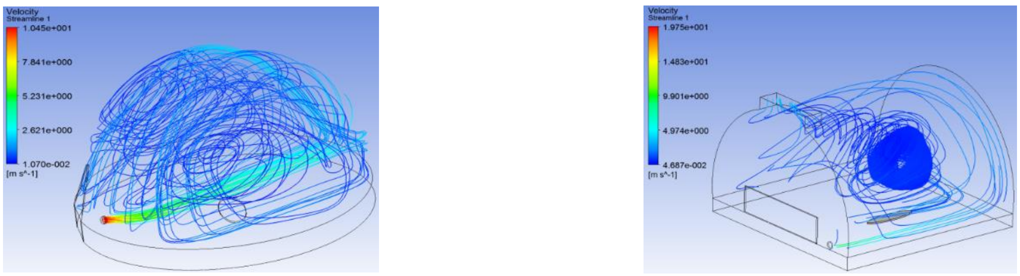
Due to fulfill this demand two different configuration are simulated and their obtained numerical results were compared with experimental measurments. Figures 5a and 5b illustrate streamlines in Sangak and Barbari bakeries, respectively.

The empirical measurments reports that in Sangak bakery inlet hot flow has a collision with the back wall (the wall that is in front of aperture) and then distribute in oven irregularly.

Because of this irregular fluid flow, temperature distribution is Sangak oven is uniform. On the other side, based on experiments, temperature of bach section of Barbari oven is more than other sections. This is why the hot gases flow after collision to back wall dows not distribute in oven, but also gang up on back section of oven. Based on Figure 5, all of these phenomenons are observeed in numerical solution results. Therefore, in problem of fluid flow, there is a remarkable coincidence between numerical and empirical results. But the main note in this paper is to validate these numerical models for analysis and investigation different heat transfer portions in baking ovens. Accurate cognition of the portions of different mechanisms of heat transfer during the baking process is important and it can introduce useful solutions to improve quality of breads and reduce energy consumption of oven, such as optimization of furnace geometry, thermophysical and radiative properties of the furnace. The important point in optimization of bakery ovens is that the basis should be the bread quality and the optimized factors that keep the quality of bread should be considered as the optimization model. In this optimization field, natural gas consumption reduction is the second important issue. In order to provide quality of bread, the most important condition is that receive energy by bread from up (radiation and convection) and down (conduction) should be the same with each other. Table 8 reports the portions of different mechanisms of heat transfer during baking process of different breads based on empirical results. The obtained results showed that in Sangak and Barbari bakeries portions of convection heat transfer mechanism and volume radiation are negligible against of conduction and surface radiation mechanisms.

Therefore, improvement of convection mechanisms and volume radiation can not enhance energy consumption in oven and investigatore should focus on improving surface radiation and conduction technichs in these ovens due to reduce fuel consumption. Finally, Table 9 compares numerical and empirical results in term of share of different heat transfer mechanisms during baking process.

This table shows that numerical solution can make a reliable result in case of modeling bakery ovens, because of a good agreement between numerical and experimental results with the maximum error of 12.57% for Barbari bakery and 11.69% for Sangak bakery.



(a) (b)

Figure 5. Illustration of streamlines in (a) Sangak, and (b) Barbari ovens

TABLE 8. The portions of different mechanisms of heat transfer during baking process

Different heat transfer mechanisms (%)	Bakery	
	Sangak	Barbari
Forced convection	0.32	0.46
Natural convection	5.24	4.71
Convection	5.56	5.17
Conduction	44.52	43.29
Volumetric radiation	8.01	3.74
Surface radiation	41.91	47.80
Radiation	49.92	51.54

TABLE 9. The comparison between experimental and numerical

Bakery	**Type of results**	**Different heat transfer mechanisms**		
		Convection	**Conduction**	**Radiation**
Sangak	Exp.	5.56%	44.52%	49.92%
	Num.	6.21%	46.53%	47.26%
	Error	11.69%	4.51%	5.33%
Barbari	Exp.	5.17%	43.29%	51.54%
	Num.	5.82%	45.83%	48.35%
	Error	12.57%	5.87%	6.19%

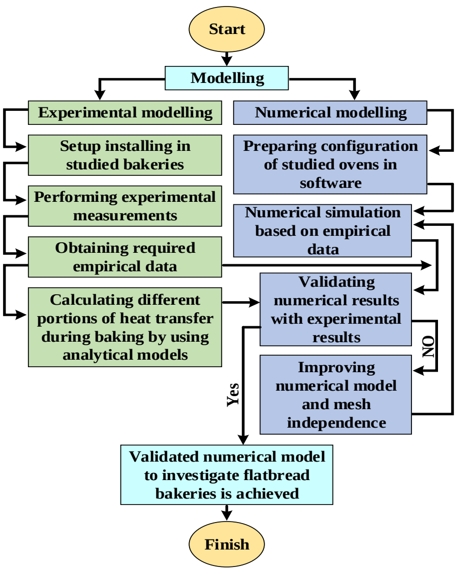


Figure 6. The flowchart of solution in this paper

However in the both ovens, the max values of errors are related to convectionheat transfer and it is while th portion of this mechanism is negligible against of conduction and radiation. Therefore, the actual error of this validation can assume less than above values. Figure 6 illustrates flowchart of solution in this paper.

5. CONCLUSION

In this investigation, experimental measurements and mathematical modeling were employed to investigate the different parameters in two different Iranian traditional flatbread bakeries. The main aim of this study was introduction of a numerical simulation in order to validate and investigate the flatbread bakery ovens. Due to fulfill this demand two numerical models were used and solved using control volume method based on SIMPLE algorithm and RNG k-ε method. In all studied ovens, the bread receives the energy from convection (natural and forced convection), conduction, and radiation (volumetric and surface radiation). The results revealed that the share of convection in baking Sangak and Barbari is insignificant and it is possible to neglect it comparing to conduction and radiation. The share of different heat transfer mechanisms in baking traditional bread are as follows: Sangak: conduction 44.52%, radiation 49.92%, and convection 5.56%; Barbari: conduction 43.29%, radiation 51.54%, and convection 5.17%. The accurate recognition of different heat transfer mechanisms share in baking different bread, leads to suggesting solutions to improve bread quality and fuel consumption decrease. Therefore the optimization of thermophysical and radiative properties of various furnaces walls has an important role in saving fuel consumption and improving the bread quality. Finally, the obtained results of numerical simulation showed that numerical solution can make a reliable result in case of modeling bakery ovens, because of a good agreement between numerical and experimental results with the maximum error of 12.57% for Barbari bakery and 11.69% for Sangak bakery.

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Experimental and Numerical Investigation of Two Different Traditional Hand-Baking Flatbread Bakery Units in Kashan, Iran

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چکیده

در پژوهش پیش‌رو پیرامون دو نوع از تنورهای دست‌پز پخت نان سنتی مسطح سنتی (سنگک و بربری)، با استفاده از آزمایش‌های تجربی و شبیه‌سازی عددی، پارامترهای مختلفی مانند دمای قسمت‌های مختلف تنور، مصرف گاز طبیعی، دمای گازهای خروجی از دودکش و سهم مکانیزم‌های مختلف انتقال‌حرارت در پخت نان مورد بررسی قرار گرفته‌اند. هدف اصلی کار حاضر معرفی یک روش عددی مناسب برای شبیه‌سازی و مطالعه تنورهای سنتی پخت نان سنتی مسطح است. بدین منظور تنورهای دست‌پز پخت نان سنگک و بربری مدل‌سازی شده و نتایج حاصل از شبیه‌سازی عددی با نتایج نجربی حاصل از آزمایشات اعتبارسنجی شده‌اند. نتایج حاصل از اعتبارسنجی نشان‌دهنده اعتبار مناسب و قابل قبول مدل عددی ارائه شده در کار حاضر به منظور مطالعه تنورهای نانوایی سنتی پخت نان سنتی مسطح با حداکثر خطای ٪12/57 است.

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