LCA/CFD Studies of Artisanal Brick Manufacture in Mexico

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***Abstract*—**Environmental performance of artisanal brick manufacture was studied by Lifecycle Assessment (LCA) methodology and Computational Fluid Dynamics (CFD) analysis in Mexico. The main objective of this paper is to evaluate the environmental impact during artisanal brick manufacture. LCA cradle-to-gate approach was complemented with CFD analysis to carry out an Environmental Impact Assessment (EIA). The lifecycle includes the stages of extraction, baking and transportation to the gate. The functional unit of this study was the production of a single brick in Chihuahua, Mexico and the impact categories studied were carcinogens, respiratory organics and inorganics, climate change radiation, ozone layer depletion, ecotoxicity, acidification/ eutrophication, land use, mineral use and fossil fuels. Laboratory techniques for fuel characterization, gas measurements in situ, and AP42 emission factors were employed in order to calculate gas emissions for inventory data. The results revealed that the categories with greater impacts are ecotoxicity and carcinogens. The CFD analysis is helpful in predicting the thermal diffusion and contaminants from a defined source. LCA-CFD synergy complemented the EIA and allowed us to identify the problem of thermal efficiency within the system.

***Keywords*—**LCA, CFD, brick, artisanal.

I. Introduction

THE growth of urban areas requires the development of technologies in order to use the natural resources and improve the life quality of its inhabitants. Specifically, the construction industry requires a lot of energy and resources to operate buildings and to acquire building materials.

In order to make further improvements towards the life style of a sustainable society, cleaner production must be based on the overall picture obtained from LCA [1]. Therefore, LCA should be viewed as an important tool for broadening the understanding of a product´s relationship with its environmental impact during the development process [2]. In LCA studies, outputs to the environment are quantified in order to determine the potential impacts classified into categories [3]. LCA is an analytical tool designed to assess the whole production chain of a product’s lifecycle, whereas, the EIA is a procedure that facilitates and supports the decision of a much broader range with regards to environmental aspects. It is quite feasible and that is why elements of LCA should be used in EIA [4]. Likewise, LCA is an important foundation for environmental assessment method in building. Grant and Ries [5] developed a process that incorporates service life, operational energy and LCA modelling which provides a means of examining the effects of materials and systems in building operation, maintenance, repair and replacement. Other authors have employed LCA to analyze entire building case studies [6], [7] and to examine emissions during the construction stage [8]. Kim et al. [9] evaluated the emissions due to long-life apartment buildings and Simion et al. weighs construction and demolition waste based on its ecological footprint [10].

According to the National Institute of Statistics and Geography (INEGI) [11], the 2010 census reports a housing stock of 1,228,567 houses in the state of Chihuahua, Mexico. Registering a 20% increase in 10 years. Thus, the total gross production in Mexican brick manufacture grew 10% compared to the previous year. It caused a significant environmental impact. Hence, it becomes imperative to carry out LCA in order to analyze the environmental impact of construction material manufacture throughout its entire lifecycle. Fired clay brick is a building material widely used in Latin America, India and China [17]. The brick kiln industry represents one of the major small-scale industries, which satisfies the growing demand for urban expansion [15]. These kilns may be grouped under two broad categories known as intermittent and continuous kilns. Most of the kilns around the world are traditional intermittent [14], [17], contributing to the pollution of environments and with immense disturbance potential to cause ecological alterations [15], [16]. Therefore, some researches carried out the analysis of the impacts of these brick manufacture [12]-[17].

The LCA tool considers the potential impacts on the environment, but does not consider the physical behavior of these emissions, and for this reason, this EIA study was complemented with LCA and CFD analysis.

The CFD technique involves a solution using a system of flow equations to represent the phenomenon by numerical methods. The computational simulation was performed in order to study the aeration, thermal dispersion and transportation of contaminants in urban areas, isolated buildings, as well as to examine the effects on adjacent buildings. Turbulence Reynolds-averaged Navier–Stokes

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Models (RANS) have been used for this purpose, those models are: k-ε Realizable model [18], [19], k-ε Standard model [20], [21], or k-ε Renormalization Group model (RNG) [21], [22] and the Large-Eddy model for turbulence dynamic [23], [24]. The CFD tool has been also used to describe the toxicity risk of chemical gases trough the simulation of accidents [25], [26]. CFD software was used successfully to simulate the dispersion of particulate matter emitted during the injection of biosolids on a farm field; many researches are constantly applying CFD techniques to solve new and more complex air quality problems [27].

This paper covers the analysis study of the environmental performance of artisanal brick manufacture in Mexico by combining LCA and CFD methods. The impact categories assessed in this study records three types of damage: Damage to human health, damage to ecosystem quality and damage to resources. This is complemented with a CFD application to predict the physical performance of the hot gas stream.

II. Materials and Methods

A. Case Study

Fig. 1 shows a description of the traditional brick manufacturing process. The clay is extracted from a local clay deposit by a backhoe, then it is transported to the baking stage zone by a dump; the mixing clay with water, and the brick molding stages are done manually. The bricks are dried in the sun and the firing process was conducted in a traditional intermittent kiln (Fig. 2), which operates with residual sawdust as fuel.

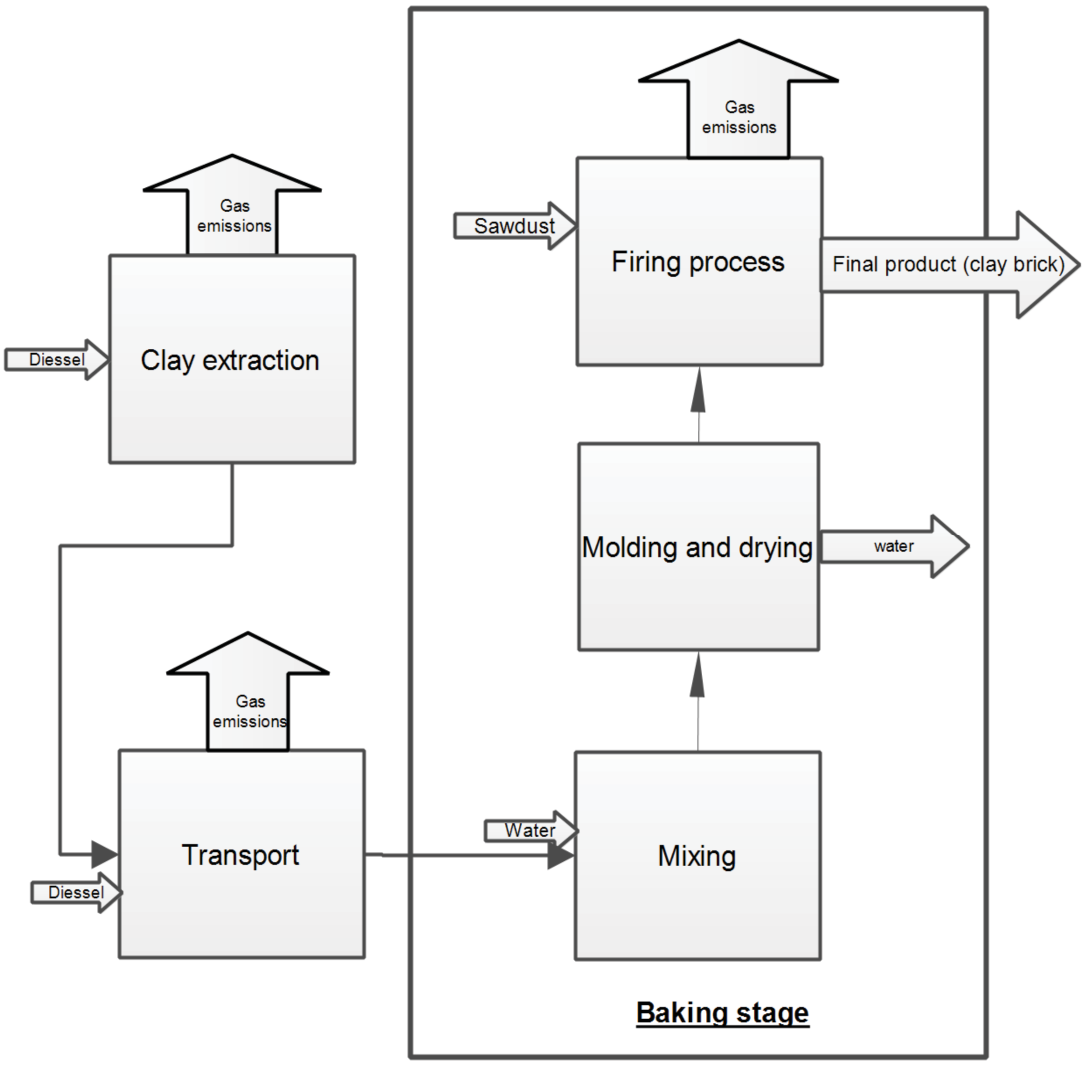

Fig. 1 Brick manufacturing process

In this study, the system boundaries include clay extraction, water consumption and its transportation to the manufacturing process, and the baking stage.

B. Life Cycle Assessment

LCA is a methodology based on the compilation and evaluation of inputs, outputs and the environmental impacts of a production chain through its lifecycle. LCA studies include four phases: goal and scope definition, inventory analysis (LCI), impact assessment and interpretation [28].

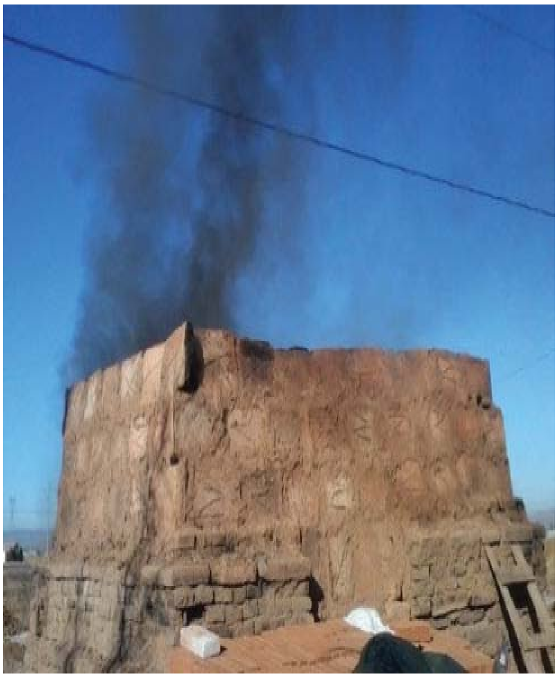

Fig. 1 Traditional Mexican kiln

C. LCA Goal and Scope Definition

The LCA was done following ISO 14040 2006 and ISO 14044 2006 standards [28], [29]. The goal of this LCA study is to determine the potential environmental impact of the artisanal brick manufacture process using a cradle-to-gate approach for traditional combustion process manufacture.

The functional unit is the basis for the comparison of different systems; its primary purpose is to provide a reference in which the inputs and outputs are related [28].

The production of a single brick in Chihuahua-Mexico was defined as the functional unit, as it is a reference measurement of commercial sale in the formal and informal construction sectors.

The standard size of the brick is 7 cm, 14 cm, 28 cm. It was manufactured with 1.29 kg of clay and 200 ml of water, firing 0.87 kg of residual sawdust for 16 hours at a temperature of 900 ºC. Its production was carried under traditional operating conditions in an intermittent kiln with a 17,000 brick capacity, which contributes greatly to pollution and environmental deterioration [17].

D. Life Cycle Inventory Analysis

According to the system boundaries, LCI was mainly based on the input and emission output data from Table I. The raw material and sawdust consumption was provided by regional artisanal brick producers. The LCI emission data for the clay extraction and transport stage was calculated using AP42 emission factors (EPA 2009) [30]. The considered distances were: i)14.6 km from the extraction zone to the brick production zone, ii) 9.36 km from the water supply zone to the brick production zone and iii) 14.65 km from the sawdust production zone to the brick production zone.

Regarding emissions of the brick manufacturing process, analysis of the gas furnace in situ using the TESTO Model 330-LI gas analyzer was carried out in order to measure the CO_2, CO and O_2 concentrations using the principle of ion selective potentiometry (Electrochemical sensors). The NOx emissions were calculated in a Shimadzu model NOA 7000 using the normal pressure chemoluminescence method.

A sample of 1.24 g sawdust (fuel) was evaluated in a gas chromatograph CE EA110 instruments mod according to ASTM D5373 (For C, N and S). Chlorine content was determined by Argentometry.

E. LCA Analysis Assumptions and Limitations

The following conditions were assumed in order to calculate the mass balance of sawdust combustion (1):

- The elemental nitrogen found in the fuel and nitrogen present in air was converted to NOx in order to perform the calculations.
- Polychlorinated compounds are represented as 2,3,7,8 Tetrachlorodibenzo-p-dioxin. Generation of polychlorinated compounds is due to the amount of Chlorine present in sawdust. We assume that all Chlorine becomes part of the polychlorinated compounds as the worst case scenario.

Equation (1) shows the mass balance that was used to predict average concentrations of output gas mixture and to calculate the gas emissions inventory for the brick manufacturing process.

$$\{\text{Raw clay brick}\} + \{H_2O\} + \left\{\begin{matrix}\text{Fuel:}\\ \text{sawdust:}\\ (C, N, Cl)\end{matrix}\right\} + \left\{\begin{matrix}\text{Air}\\ (N_2, O_2)\end{matrix}\right\} = \{\text{Fired brick}\} + \left\{\begin{matrix}\text{Combustion gases}\\ \left(\begin{matrix} CO_2, CO, O_2, N_2,\\ \text{Polychlorinated, and } NO_x\end{matrix}\right)\end{matrix}\right\} + \{H_2O\} \quad (1)$$

F. Environmental Impact Assessment

For the impact assessment, the endpoint impact category of the Eco indicator 99 methodology has been used using SimaPro 7.3 Software and Eco-invent v3.1 database parameters. The Eco indicator methodology models the cause-effect chain up to the damage. It includes the impact categories: carcinogens, respiratory inorganics, organics, climate change, radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication, land use, mineral use and fossil fuels.

G. Computational Fluid Dynamics

An academic version of CFD Ansys-Fluent 15.0 software was employed to create a computational model for the traditional arrangement inside of the kiln and the thermal diffusivity of the combustion gases prediction. The governing equations are obtained by applying the fundamental laws of physics to fluid motions: conservation of mass, conservation of momentum and conservation of energy. These equations are a set of coupled and non-linear partial differential equations;

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the CFD studies are used to obtain a computer based approximate numerical solution for a particular situation.

In order to describe the diffusion and transport of chemical specie a steady state model was considered. When the kiln reached the normal operation conditions, an average monthly air current of 21 kilometers per normal hour at the top of the kiln was considered. A turbulence k-ε RNG of the two equations model was used based on the turbulence (k) kinetic energy transport and its dissipation (ε). This turbulence model is derived from the Navier-Stokes equations using the group renormalization mathematical technique. This CFD code solves the RANS governing equations using the finite volume method. The operation conditions for the simulation were g = -9.81 m s-2, pressure and temperature were: 101.32 KPa and 288.16 K.

III. Results and Discussion

The fuels and emission gases were characterized at the laboratory and in situ in order to develop an appropriate LCI (Table I). Sawdust elemental chemical analysis by GC technique showed a weight content (%) of: 47.92 carbon, 3.47 nitrogen. The chlorine that was detected (0.03 %) by the Argentometry method is attributed to chemical wood treatment with pentachlorophenol. It could produce dioxin emissions, in this study it is estimated with (1). Sulphur oxide emissions were not evaluated since Sulfur was not detected in the elemental analysis. The CO, CO_2, O_2 and NO_x emissions, were determined using the fuel inlet and the percentage of concentrations measured with the gas analyzer.

Sawdust combustion provides other pollutants such as fine dusts. Since the furnace design studied does not have an implemented bell to concentrate the particles emitted by the chimney, it is not possible to carry out the measurement of these fine particle emissions on-site.

The life cycle impact assessment phase includes the assignment of the LCI results to selected impact categories and the calculation of the potential environmental impacts in each category. In this study, the environmental impacts categories considered were carcinogens, respiratory inorganics, organics, climate change and radiation from the Human Health damage category, expressed as the number of year life lost and the number of years lived disabled, using DALY units (Disability Adjusted Life Years). Radiation, ozone layer depletion, ecotoxicity, acidification/eutrophication and land use categories from ecosystem quality, expressed as the loss of species over certain area, over a certain time, by PDF*m2yr units (Potentially Disappeared Fraction of plant species per square meter and year). The minerals and fossil fuel categories are present in energy source damage expressed as the surplus energy needed for future extractions of mineral and fossil fuels, by MJ surplus (Mega Joules). The results of the LCA are shown in Table II and Fig. 3.

LCA considers the environmental impacts, but does not represent the physical behavior of gas flow and temperature. To consider both perspectives, the physical performances were numerically simulated with computational CFD analysis in steady state.

TABLE I
LIFE CYCLE INVENTORY ANALYSIS

Burning time (hrs.)		***16:00***
Inputs	Unit	Amount
Water *(kg)*	*kg*	0.20
Water transport *(kgkm)*	*kgkm*	1.87
Clay *(kg)*	*kg*	1.29
Clay transport *(kgkm)*	*kgkm*	18.96
Sawdust *(kg)*	*kg*	0.87
Sawdust transport *(kgkm)*	*kgkm*	12.70
Air *(kg)*	*kg*	11.14
Outputs	*Unit*	Amount
Carbon dioxide (CO_2)		1.29
Carbon monoxide (CO)		8.5E-3
Oxygen excess (O_2)		3.34
Nitrogen (N_2)	kg	11.11
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-		0.14
Nitrogen oxides (NO_X)(ppm)		354.7
Water (H_2O)		3.25

TABLE II
RESULT VALUES FOR LCA ENVIRONMENTAL IMPACT AND DAMAGE CATEGORIES

Impacts categories	Unit	Values
Carcinogens	DALY	19.332
Respiratory organics	DALY	2.26815E-07
Respiratory inorganics	DALY	4.55081E-06
Climate change	DALY	2.15792E-07
Radiation	DALY	6.62186E-12
Ozone layer	DALY	6.50855E-13
Total Human Health	DALY	19.33200499
Ecotoxicity	PDF*m2yr	142560.0011
Acidification/ Eutrophication	PDF*m2yr	0.291204193
Land use	PDF*m2yr	0.000746268
Total Ecosystem Quality	PDF*m2yr	142560.293
Minerals	MJ surplus	3.97183E-05
Fossil fuels	MJ surplus	3.91284E-05
Total Resources	MJ surplus	7.88467E-05

The operating conditions that control the diffusion of contaminant gases was identified by CFD. In order to identify them, the CFD analysis required the main variables such as pressure, temperature, velocity, turbulence, and species concentration. In this work, the gas velocity, temperature and CO_2 mass fraction profiles were considered (Figs. 4-9).

The model works with $1.85e^6$ elements. The overall profiles that were analyzed identified that the traditional brick's arrangement is an inefficient energy transfer process. Therefore, it is a polluting process and its impacts were demonstrated by the LCA. The gas velocity vector field, presented in Figs. 4-6 show the preferential trajectory flow of combustion gases, the temperature profiles and CO_2 mass fraction distributions, respectively.

For this case study, the energy production comes with gas emissions, however CFD analysis indicates how the energy contained in combustion gases is used for firing bricks and LCA quantifies the relevance of the manufacturing process.

The CFD simulation shows that is necessary to design a new way to accommodate the bricks inside the kiln to take advantage of the gases circulation, to make its thermal profiles uniform and improve the bricks quality while reducing their cost.

TABLE III
COMPARISON OF CO_2 EMITTED BY TRADITIONAL BRICK KILN AND TUNNEL BRICK KILN IN GREECE

Scenario location	**Chihuahua, Mexico**	**Tessaloniki, Greek**
Technology	Traditional brick kiln	Tunnel brick kiln
Capacity (bricks per year)	816,000	1,242,600
Fuel type	Sawdust	Pet coke
Kg-CO2 per brick	1.29	1.20

Table III shows a comparison of traditional brick kiln technology (sawdust as fuel), and tunnel brick technology (pet coke as fuel) applied in Tessaloniki, Greece [31]. Both scenarios have approximately equivalent emissions of CO_2. Although, biomass (sawdust) is supposed to be a cleaner fuel than pet coke, both studies show similar CO_2 emissions. Moreover, any of the reviewed LCA studies, consider the category of carcinogens (or impacts related to polychlorinated emissions) in their impact analysis [7], [32], [33]. Table IV shows a comparison of the carcinogens and ecotoxicity categories of the present study and another carried out in India [34]. Traditional brick manufacture in Chihuahua has a bigger impact, related to the polychlorinated compounds emitted from the firing process.

TABLE IV
COMPARISON OF THE CATEGORIES RELATED TO POLYCHLORINATED EMISSIONS IN THE STUDY

Impact category	Maharashtra, India	Chihuahua, México
Carcinogens	4.56E-03	19.332
Ecotoxicity	7.74E-05	142 250.00

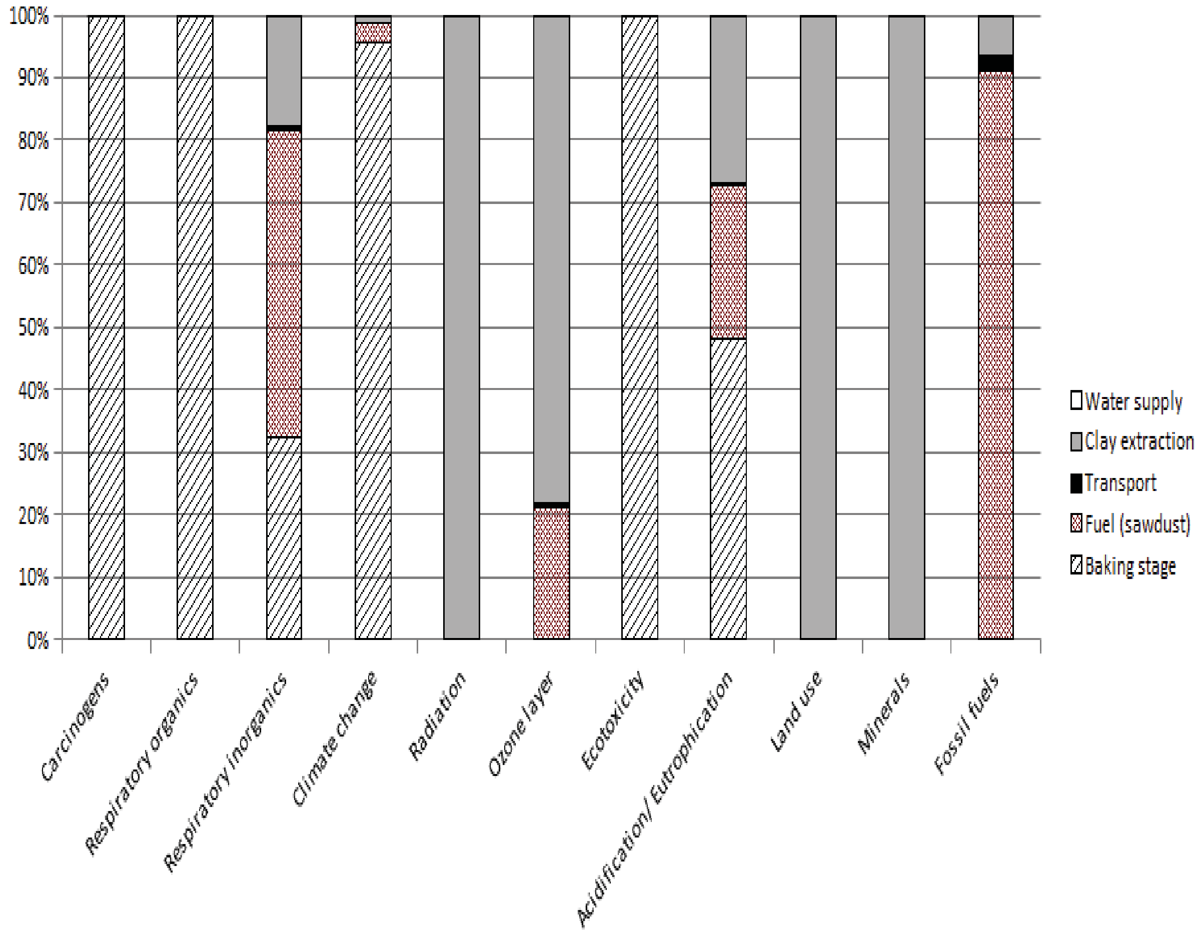

Fig. 3 Life Cycle Impact Assessment of brick manufacturing

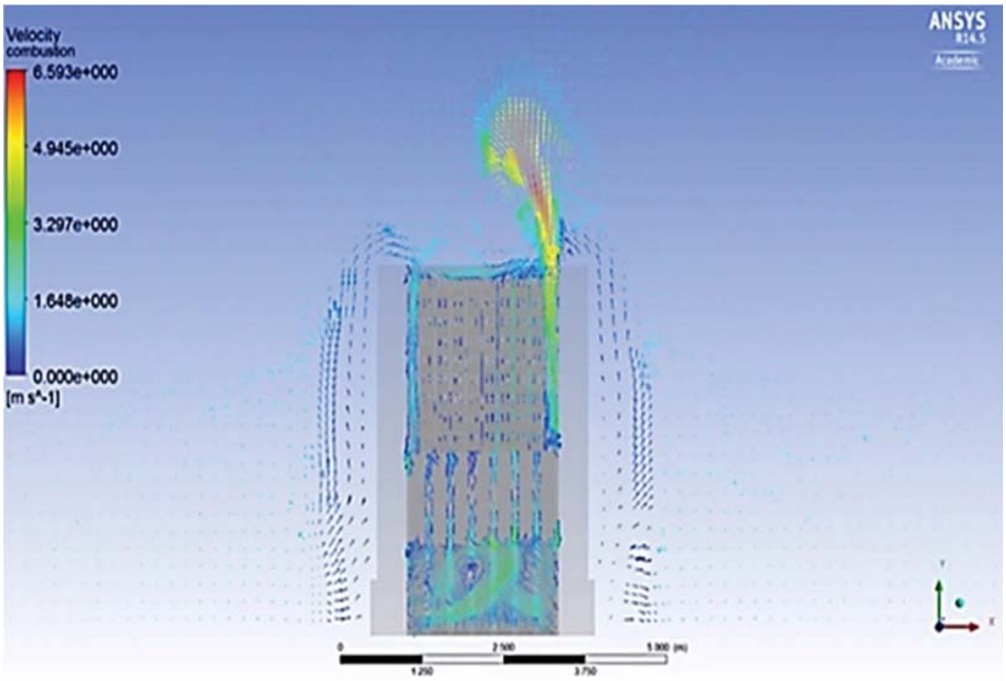

Fig. 4 CFD velocity vector field

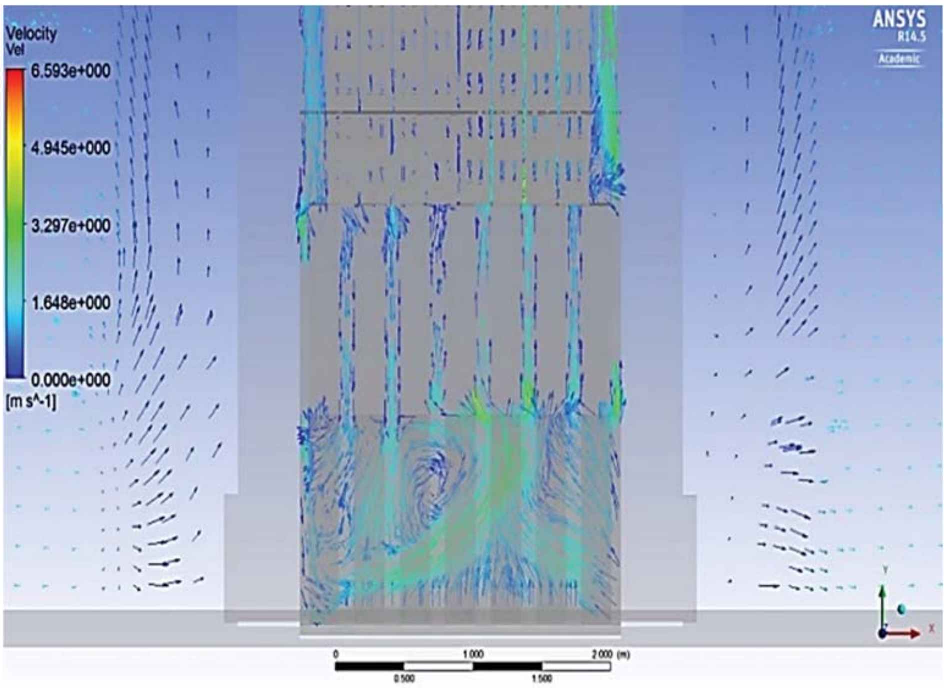

Fig. 5 Kiln from the figure zoom

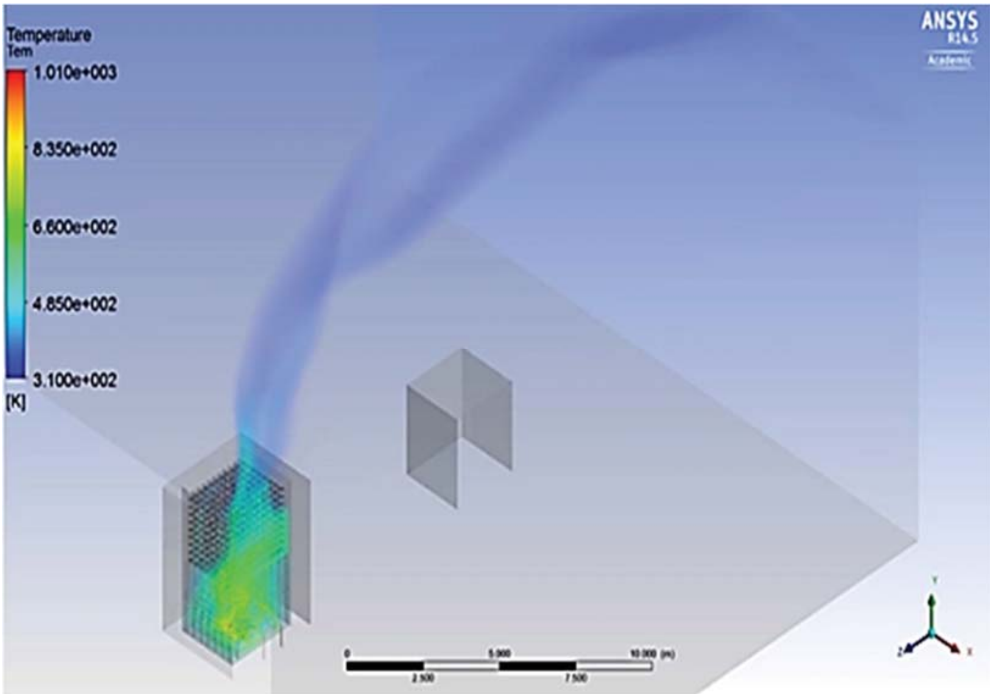

Fig. 6 CFD temperature profile

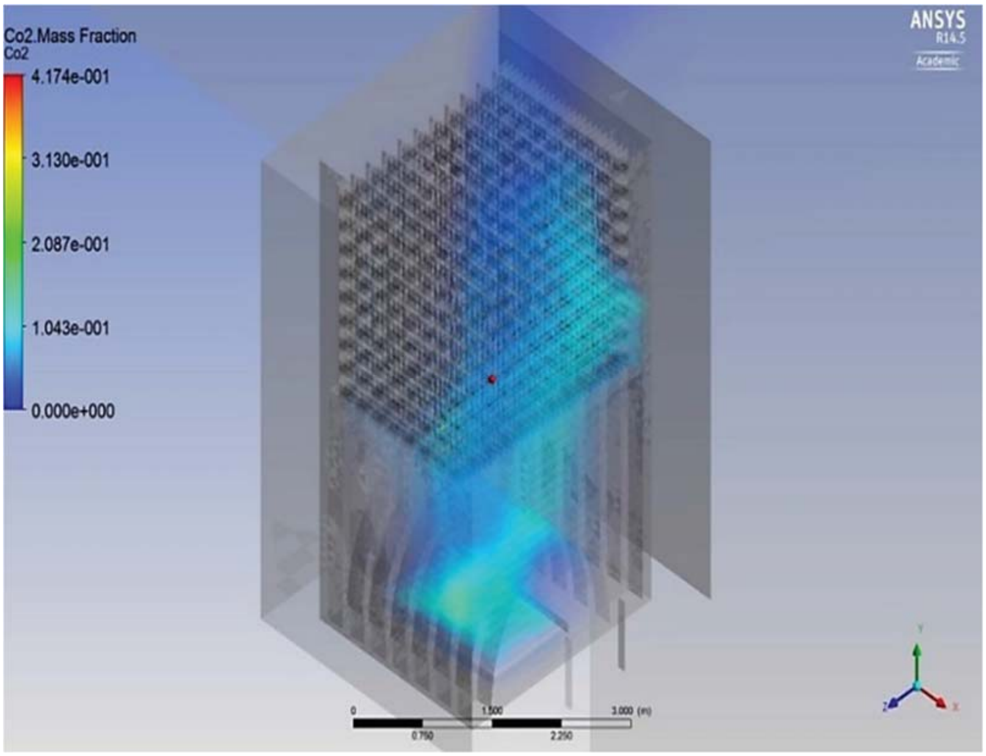

Fig. 7 CFD Kiln from the figure zoom

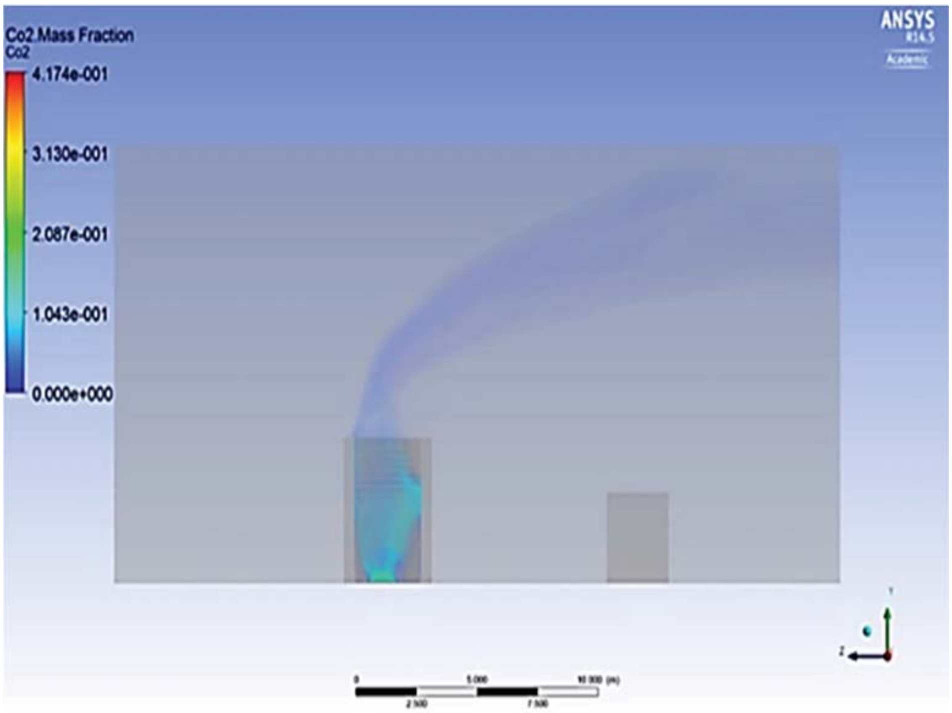

Fig. 8 CFD CO_2 mass fraction profile

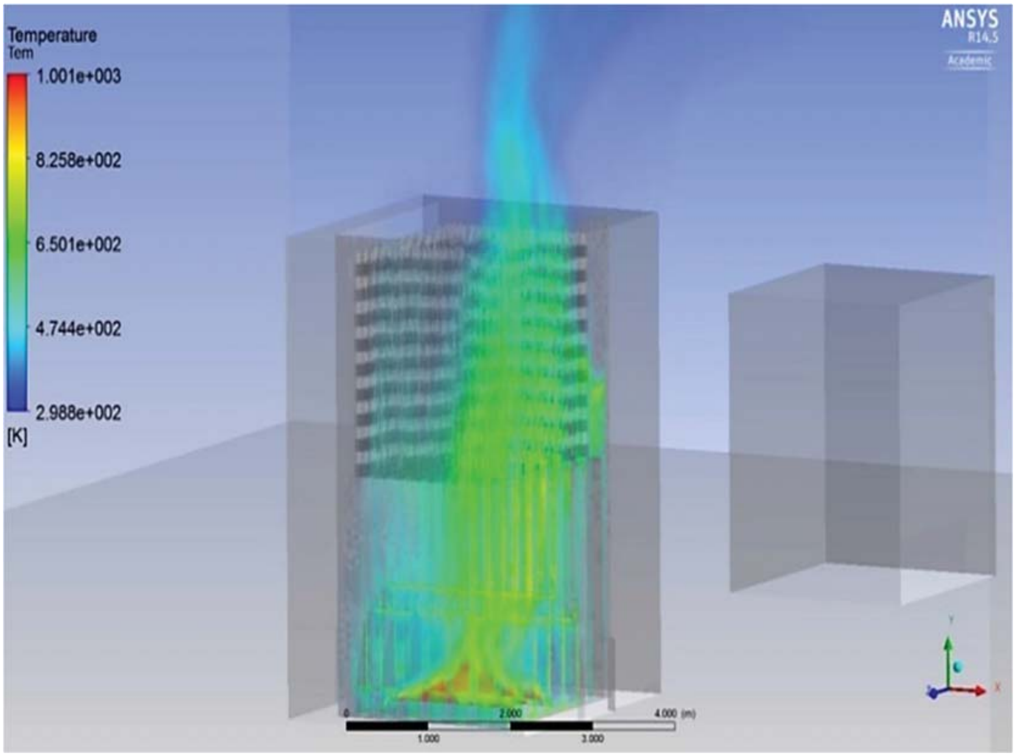

Fig 9 Kiln from the figure zoom

IV. Conclusion

The study assessed the environmental impacts of the traditional brick manufacture in Mexico. From a lifecycle perspective, the main contributors to the potential environmental impacts are clay extraction and the firing process. The results indicated that the greatest quantified contribution corresponds to the human health damage category. The polychlorinated emissions are the principal contributor to the carcinogens category.

The LCA and CFD methodologies contributed to the analysis of the local traditional scenario. LCA-CFD synergy enabled the EIA from different perspectives and allowed it to identify areas of opportunity. Furthermore, an improvement in the traditional process, could lead to a meaningful reduction in the environmental impacts. Moreover, it is important take into account the bricks array in the firing process and the combustion phenomenon too, in order to generate a homogeneous temperature field.

The inventory information contributes to develop the national life-cycle inventory (LCI) database. The considered data are representative of the Mexican brick production.

The environmental and health impacts that are generated by the brick industry will enable the support of the relevant authorities in order to comply with international treaties, where Mexico is highly committed to monitoring and promoting alternative solutions.

Future research could focus on the analysis of dioxins in soils introduced via atmospheric deposition from the brick manufacturing.

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- **An optical overview of Ploy [m2-L-alanine - m3-nitrato-sodium (I)] crystals** E. Gallegos-Loya, E. Orrantia Borunda and A. Duarte Moller. *The Scientific world Journal.*, No.:2012, Vol:.2012, Pp.:7
- **SnO2 thin films grown by pulsed Nd:YAG laser deposition** E. Chan y Díaz, A. Duarte Moller and F. Román
- *Applied Physics A Materials*, No.:, Vol:.106, Pp.:619
- **Cytotoxicity of carbon nanotubes on J774 macrophages is a purification dependent effect** Silvia Lorena Montes-Fonseca, E. Orrantia-Borunda, A. Duarte-Moller, Antonia Luna-Velasco, Manuel Román-Aguirre, Carmen González-Horta and B. Sa´nchez-Rami´rez *Journal of Nanomaterials.* No.:2, Vol:.8, Pp.:167-181

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