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Thermodestruction of wastes generated by the thermal processing of household wastes: Thermal study of the equipment in turbulent regime

Kalifa Palm[1*], Issaka Ouedraogo[1], Kokou N'Wuitcha[2], Michel O. Zongo[3], Alioune Ouedraogo[3] and Belkacem Zeghmati[4]

[1]Institut de Recherche en Sciences Appliquées et Technologies 03 BP 7047 Ouagadougou 03, Burkina Faso
[2]Université de Lomé BP 1515 Lomé, Togo
[3]Université de Ouagadougou 03 BP 7021 Ouagadougou 03, Burkina Faso
[4]Université de Perpignan 52 Avenue Paul Alduy, 66860 Perpignan Cedex, France

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ABSTRACT

In this work, we conduct a thermal study on the installation of an incinerator of gas generated by the carbonization of household wastes. We used forced and turbulent flows, with Reynolds number ranging between 5,000 and 20,000. This combustion phenomenon is handled with Navier-Stokes equations, those on the energy and distribution of the species contained in smokes to which we associate k-ε closure model. To handle this combustion phenomenon, we use the FLUENT code that directly integrates all the equations on turbulence, k-ε model for the equating and discrete ordinates model for radiative transfers. Temperatures, around 600 K for a Reynolds number of 5,000, decrease when Reynolds number increases. Results show that highest temperatures are found near the walls of the incinerator. Given the quantity of energy released in these areas, thermal recovery is possible, but this must be properly done to minimize losses.

Keywords: incineration, turbulence, combustion, temperature, thermal recovery

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INTRODUCTION

These recent decades have been characterized at the environmental level, by a steady increase in quantity and types of wastes, and whatsoever the country. This may be due both to industrial activities, with the growing urbanization and the development of a number of synthetic products related to new types of wastes. The municipal wastes include the following:

- Household wastes produced by household activities ;
- Jumbling wastes and small rubbles ;
- Wastes generated by car industry ;
- Wastes generated by the maintenance of green areas ;
- Mud generated by water purification plants ;
- Wastes from individual sanitation ;
- Various quantities of toxic wastes disseminated and lastly special wastes.

This paper deals particularly with household wastes. They constitute, for example, two-thirds of municipal wastes in France. Thus putrescible volume and the quantity of papers / cardboards included in these wastes are relatively high with 28.8% and 23.5% of the volume of household wastes respectively [1].

The amount of waste produced is often the result of consumption patterns. This varies by country depending on its level of development and income. A study conducted by The World Bank in 1982 shows that the quantities of various types of household wastes produced in large cities in various countries may vary widely based on the average annual income per capita [2]. Wastes disposal chain comprises four steps :

- The collection ;
- The transportation to waste processing site ;
- The actual processing ;
- The storage of finite wastes.

The treatment systems strive to make residues from human activities eco-friendly, by reducing the outflow toward the external environment and by properly stabilizing substances contained in wastes. The sound knowledge of the technology of waste combustion in closed stoves is new. Indeed, the first municipal waste incinerators in Europe appeared in late 19th century. This technology was then developed with the steady increase in the quantity of wastes produced during the whole 20th century [1]. In the proposed thermal treatment, we distinguish incineration which aims to reduce into ashes (etymologically "in ciner") and energy valorization, which consists in producing energy from wastes to reuse as heat or electricity.

The incineration of household wastes is a highly polluting activity. Indeed, 90% of the initial mass is in smokes and reduced into dust, pollutant gas and condensable organic compounds that develop in smoke. The high concentration of pollutants [3] that impacts on the environment and the toxicity of smokes released from incineration [4] require treatment prior to any discharge [5].

In the management of smokes from incineration [6], we investigate how to develop energy generated from the combustion of these airborne effluents and under turbulent outflow conditions by using Reynolds number (Re): $5{,}000 < Re < 20{,}000$, for which the combustion of wastes is complete [7]. The cylindrical vertical incinerator has an entry and an exit located in its axis of symmetry (figure 1). Temperatures are above 600 K inside the incinerator and decrease when the Reynolds number increases [8]. This combustion is handled by the Navier-Stokes equations, those on energy and the distribution of species contained in smokes. To solve this combustion phenomenon, we use the FLUENT code that directly integrates all the turbulence equations, the k-ε model to equate and the discrete ordinate model for radiative transfers [9].

NOMENCLATURE

U: Radial speed component (m/s)
V: Axial speed component (m/s)
T: Temperature (K)
Y: Mass fraction (%)
P: Pressure (N m^{-2})
c: Concentration (mole m^{-3})
ρ: Density (kg m^{-3})
μ: Dynamic viscosity (kg m^{-1} s^{-1})
C_p: Specific heat with constant pressure (J kg^{-1} K^{-1})
λ: Thermal conductivity (W m^{-1} K^{-1})
σ: Speed of appearance and disappearance of species (s^{-1})
k : Turbulent kinetics (m^2/s^2)
ε : Turbulent kinetic energy dissipation rate (m^2/s^3)
D: Diffusion coefficient (m^2 s^{-1})
h: Coefficient of heat transfer by natural convection between the external wall and the environment (W m^{-2} K^{-1})
g: Speed up of the gravity (m s^{-2})
r: X-axis (m)
z: Y-axis (m)
t: Time (s)
H: Height of the incinerator (m)
d: Diameter (m)
Re: Reynolds number

Index :
k: Species contained in smokes
e: Entry
pi: Internal wall
pe: External wall
F: Fluid

RESOLUTION METHOD

During the incineration of smokes produced by the combustion of household wastes, transfers are described using Navier-Stokes equations, equations on energy and on the conservation of the species contained in the incinerator and the equation of radiative transfer. The model k-ε with a turbulent closing is associated with these equations. Then we make the following simplifying assumptions :

- Transfers are two-dimensional ;
- At the entry of the incinerator, smokes pre-mixed with air are assimilated to an homogenous gaseous mixture made of : CO, CO_2, CH4, HCl, H_2O, H_2, O_2, N_2, NO et NO_2 ;
- The driving pressure gradient along the horizontal axis is not considerable;
- Viscous dissipation is negligible
- Dufour and Soret effects are not considerable ;
- Physical properties of smokes are constant ;
- Smokes are incompressible and similar to a perfect gas ;
- The incinerator accepts a rotational symmetry with respect to the axis [Oz).

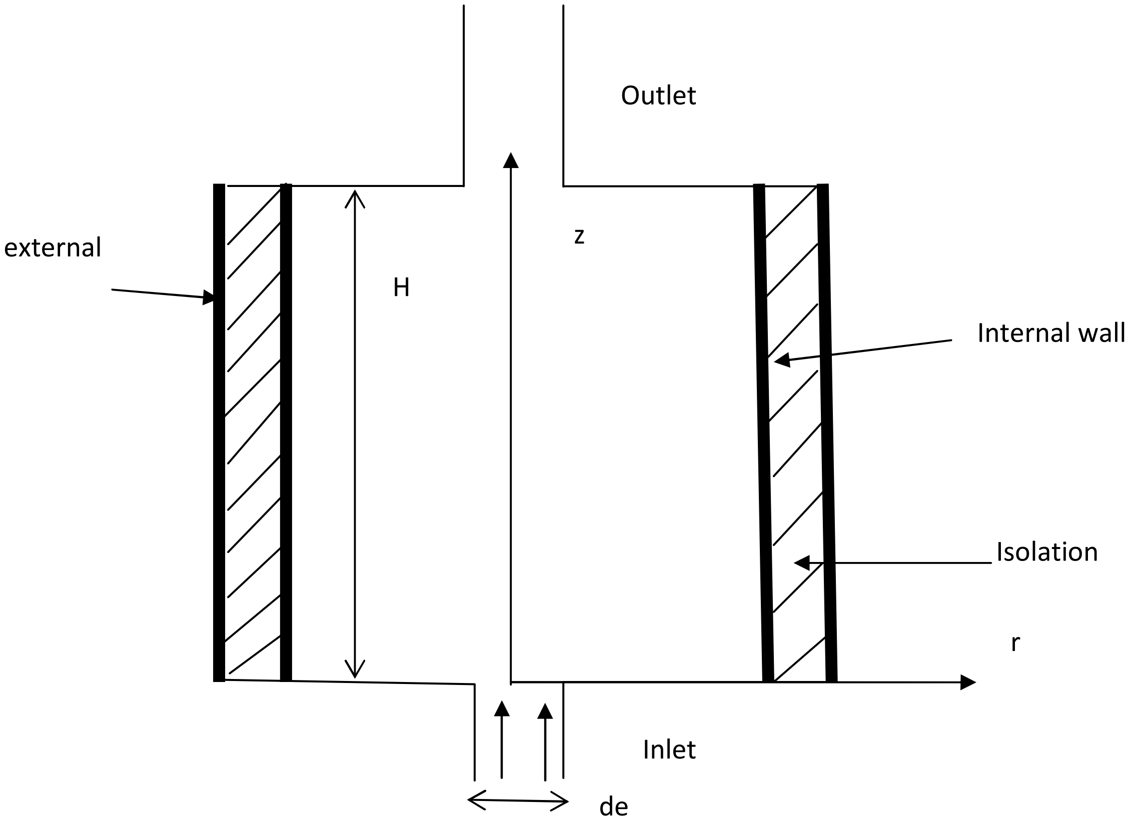

Figure 1: Descriptive outline of the incinerator model

- **Equation of the movement quantity :**

<u>Component following the axis</u> [Or) :

$$\rho\left(\frac{\partial U}{\partial t}+U\frac{\partial V}{\partial r}+V\frac{\partial U}{\partial z}\right)=\mu\left(\frac{\partial^2 U}{\partial r^2}+\frac{1}{r}\frac{\partial U}{\partial r}-\frac{U}{r^2}+\frac{\partial^2 U}{\partial z^2}\right) \quad (1)$$

<u>Component following the axis</u> [Oz) :

$$\rho\left(\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial r}+V\frac{\partial V}{\partial z}\right)=-\frac{\partial P}{\partial z}+\mu\left(\frac{\partial^2 V}{\partial r^2}+\frac{\partial^2 V}{\partial z^2}+\frac{1}{r}\frac{\partial V}{\partial r}\right)-\rho g \quad (2)$$

- **Energy Equation :**

$$\rho C_p\left(\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial r}+V\frac{\partial T}{\partial z}\right)=\lambda\left(\frac{\partial^2 T}{\partial r^2}+\frac{\partial^2 T}{\partial z^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)+Q_{rea}+Q_{rad} \quad (3)$$

- **Equation for the conservation of k species:**

$$\frac{\partial Y_k}{\partial t} + U\frac{\partial Y_k}{\partial r} + V\frac{\partial Y_k}{\partial z} = D_k\left(\frac{\partial^2 Y_k}{\partial r^2} + \frac{\partial^2 Y_k}{\partial z^2} + \frac{1}{r}\frac{\partial Y_k}{\partial r}\right) + \sigma_k \qquad (4)$$

The standard closing model k-ε per FLUENT is written as follow [9] :

- **Equation of the turbulent kinetic energy k :**

$$\frac{\partial k}{\partial t} + U\frac{\partial k}{\partial r} + V\frac{\partial k}{\partial z} = \frac{\partial}{\partial r}\left[r\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right] + \frac{\partial}{\partial z}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right] + Q - \varepsilon \qquad (5)$$

- **Equation of the dissipation rate ε of the turbulent kinetic energy :**

$$\frac{\partial \varepsilon}{\partial t} + U\frac{\partial \varepsilon}{\partial r} + V\frac{\partial \varepsilon}{\partial z} = \frac{\partial}{\partial r}\left[r\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial r}\right] + \frac{\partial}{\partial z}\left[\left(\nu + \frac{\nu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial z}\right] + C_{\varepsilon 1} Q\frac{\varepsilon}{\rho k} - C_{\varepsilon 2}\frac{\varepsilon^2}{k} \qquad (6)$$

With :

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \qquad (7)$$

$$\lambda_t = \rho C_p \frac{\nu_t}{Pr_t} \qquad (8)$$

$$D_{tk} = \frac{\nu_t}{Sc_t} \qquad (9)$$

Constants were calculated according to the following reference systems :
$\sigma_k = 1;\ \sigma_\varepsilon = 1.3$: Comparison with jet-sillage experiment.
$C_{\varepsilon 1} = 1.44$: Distortion or uniform cutting.
$C_{\varepsilon 2} = 1.92$: Isotropic turbulent decrease.
$C_\mu = 0.09$: Logarithmic law in the wall.

$$Q = 2\nu_t\left[\left(\frac{\partial U}{\partial r}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2 + \left(\frac{U}{r}\right)^2 + \left(\frac{\partial U}{\partial z} + \frac{\partial V}{\partial r}\right)^2\right] \qquad (10)$$

This closing model gives the following results in a number of practical cases [9].

Initial conditions and conditions to limits for such combustion phenomenon are as follow:

- $\forall\ \mathbf{t} \leq \mathbf{t_0}$, The incinerator is filled with smoke at rest and at the preheating temperature. The initial time t_0 corresponds to the time when the fuel mixture enters in the incinerator. Therefore, it gives :

$$U = V = 0\ ;\ k = 1\ ;\ \varepsilon = 1 \qquad (11)$$

$$T = T_0 \qquad (12)$$

$$Y_{O_2} = 0.21\ Y_{\text{air of the mixture}} \qquad (13)$$

$$Y_{N_2} = 0.79\ Y_{\text{air of the mixture}} \qquad (14)$$

Air concentration is given as follow :

$$c_{air} = \frac{\rho_{air}(T_0)}{M_{air}} \qquad (15)$$

$$Y_k = Y_{smokes} \qquad (16)$$

- **When entering in the incinerator:** $0 \leq r \leq \frac{d_e}{2}, z = 0$

We use for the speeds when entering in the incinerator :

$$V = V_0;\ U = 0;\ T = T_e;\ Y_k = Y_{ke}\ ; \qquad (17)$$

$$k_e = \frac{3}{2}(I_0 V_0)^2\ ;\ \varepsilon_e = C_\mu \frac{2\, k_e^{1.5}}{0.03\, d_e} \qquad (18)$$

- **When going out of the incinerator :** $0 \leq r \leq \frac{d_e}{2};\ z = H$

We use the "Outflow" condition of the FLUENT :
- Keeping the flow: "Flow rate weighting = 1" (19)
- Internal emissivity = 0.8. (20)
-

o **In the lateral and horizontal walls:**

We use the “Wall” condition :

- Thermal exchanges ; exchange by convection.
- Exchange coefficient with the environment : $h_{air} = 30\ W/m^2$
- Emissivity = 0.8.
- Width of the wall = 0.21 m.
- Fixed walls.
- No slip (“No slip” : shear condition) : U = V = 0
- Roughness : (height = 0 ; constant = 0.5).
- Species : $\frac{\partial Y_k}{\partial r} = 0$
- Radiations: Diffuse walls. The fluid contribute to the radiation.

Equations (1), (2), (3) and (4) together with the related initial conditions and related boundary conditions are solved using the FLUENT code , adopting the standard closure model k-ε for its easiness.

Q_{rea} is the heat released during the combustion of the various chemical species of smokes. According to Berthelot’s rule, combustion reactions are total [5]. This enables, according to that same rule, the assumption of reactions of simple and total combustion [6]. The energy released during the combustion of smokes generated by the burning of household wastes, calculated by taking the reaction rate into account, confirms the following equation [7], [8]:

$$Q_{rea} = \frac{\dot{W}_{glo}}{M} \sum_i h_i \tag{21}$$

Q_{rea} = Heat released during the combustion of species contained in the smokes.
$\dot{W}_{glo}$ = Overall speed of the fading out of species that make incinerated smoke [10]
h_i = Standard heat content of the species i at 298 K.
M = Molar mass of the incineration smokes.
i = Species contained in the incineration smokes.

RESULTS AND DISCUSSION

Data were entered into the software FLUENT. Calculations give the maximal and minimal values of isotherms as shown in figures (2), (6), (10), and (14). By changing the Reynolds number between 5,000 and 20,000 we get the following temperatures at different areas of the incinerator figures (9), (13) et (17)).

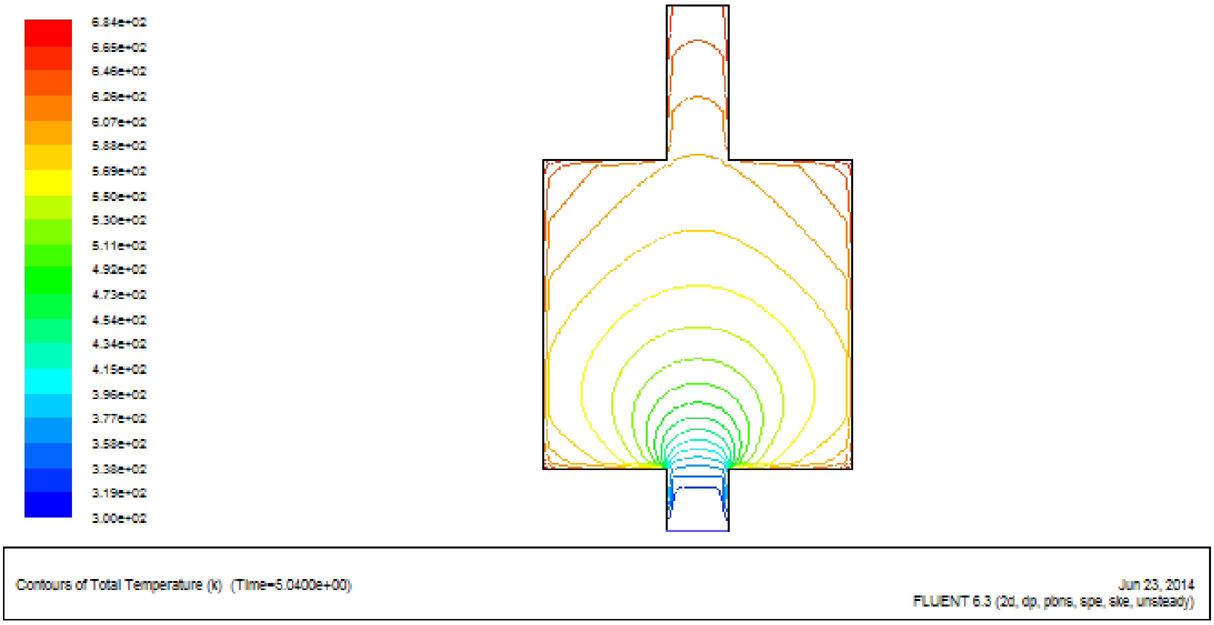

Figure 2: Isotherms with Re=5,000

We notice that the minima are located at the entry of the incinerator while the maxima are near the walls and in the chimney. These isotherms describe beams of concentric curves which go from the lower horizontal walls to closing

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thereon. For Re = 5,000, the combustion takes place near the walls. Temperatures rise to reach 684 K, which generates a large quantity of heat.

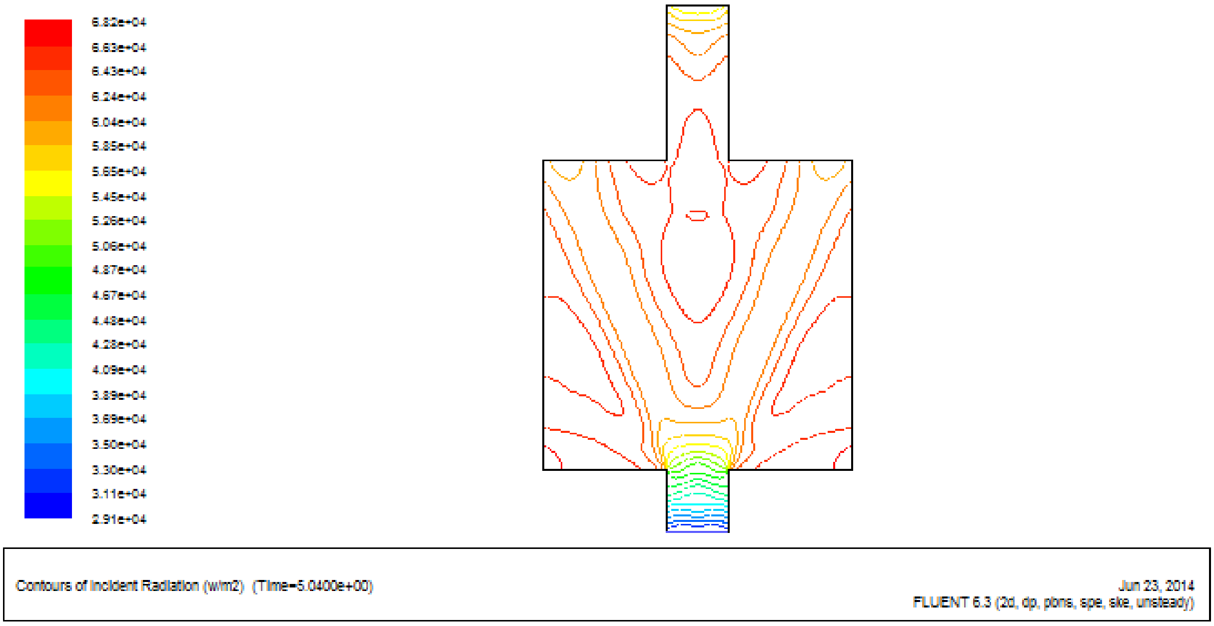

Figure 3 : Incident radiation when Re=5,000

To conduct a more detailed thermal study of this incineration phenomenon, we focus on the intensity of the incident radiation within the incinerator. The radiative activity is intense inside the incinerator and all the radiative lines end at the walls where the components of smokes burn. The maximal values of radiation reach 682 W / m^2 within the whole incinerator. The minimal values vary between 291 and 565 W / m ^{2} and are located at the entry to the system.

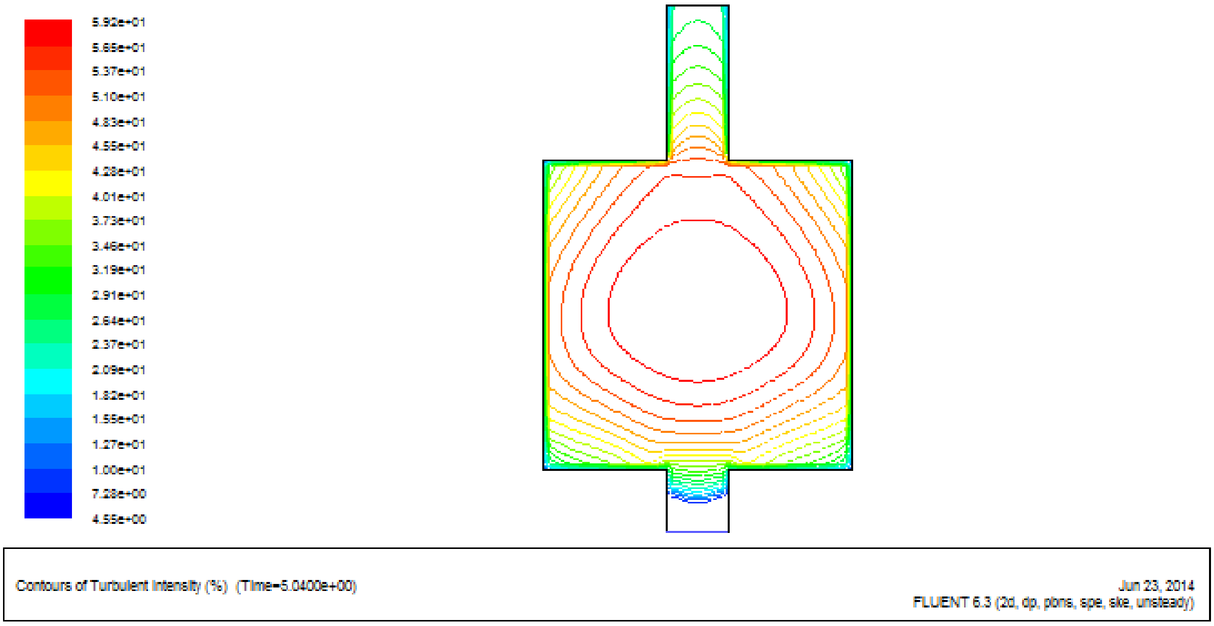

Figure 4: Intensity of the Turbulence when Re=5,000

Turbulence is intense at the center of the incinerator and reaches 59.2%, whereas it is minimal at the entry, in the chimney and in walls with values between 15.6 and 40%. This low turbulence at these areas allows a rapid increase in temperature in these areas.

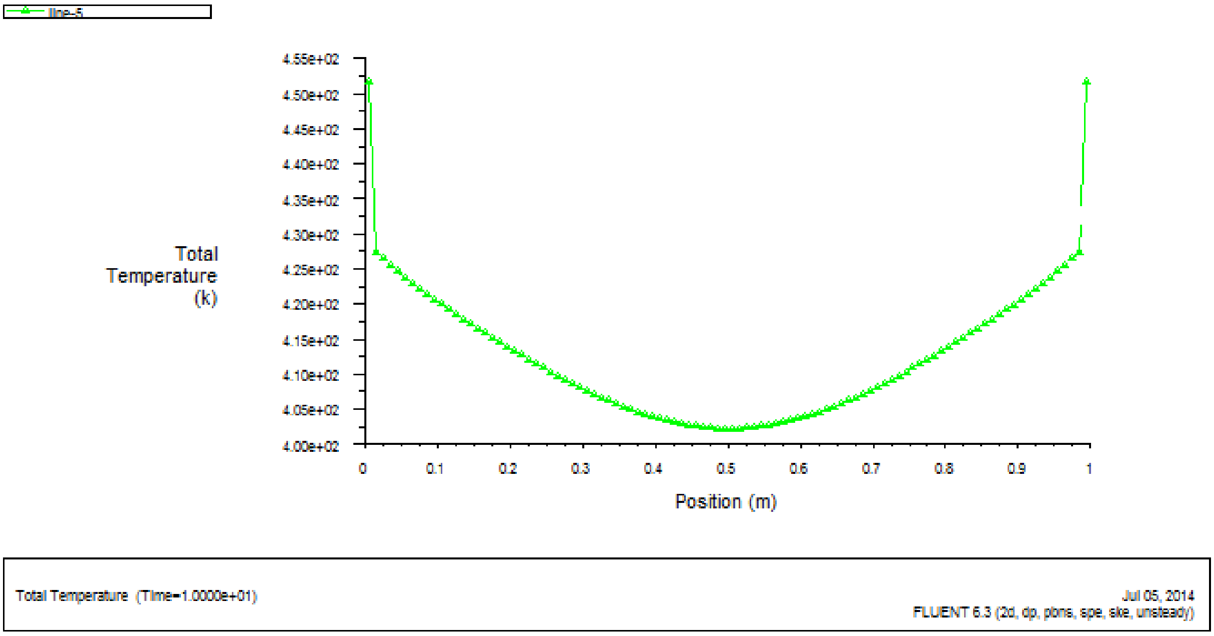

Figure 5: Variation of temperature halfway down the incinerator when Re=5,000

Temperature changes at halfway down the incinerator show that the maximal values which reach 455 K, are located near the walls where combustion occurs. The minimal values, around 400 K, are on the axis of symmetry (Figure 5). This shows that any use of the energy system must be located on the walls when Re = 5,000.

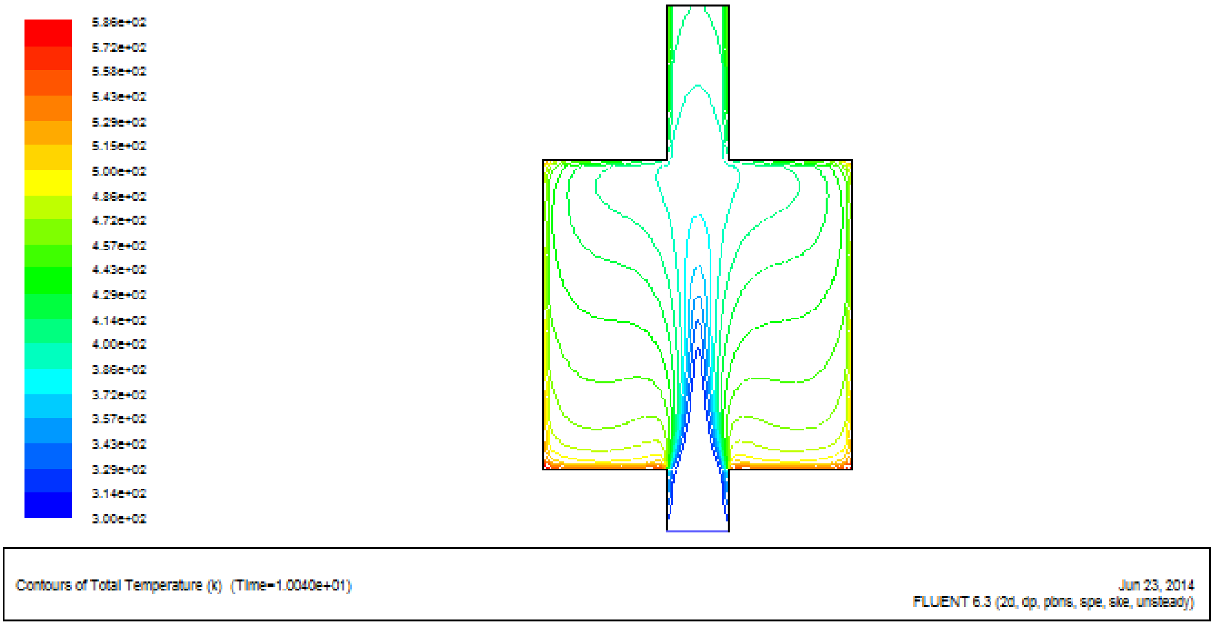

Figure 6: Isotherms when Re=10,000

When the Reynolds number, Re = 10,000, the highest temperatures are still within the walls (up to 586 K in the horizontal basis walls) and the minimal values are around the axis of symmetry (values between 300 and 400K) (Figure 6). This confirms the need to use positions near the walls to make a good use of energy.

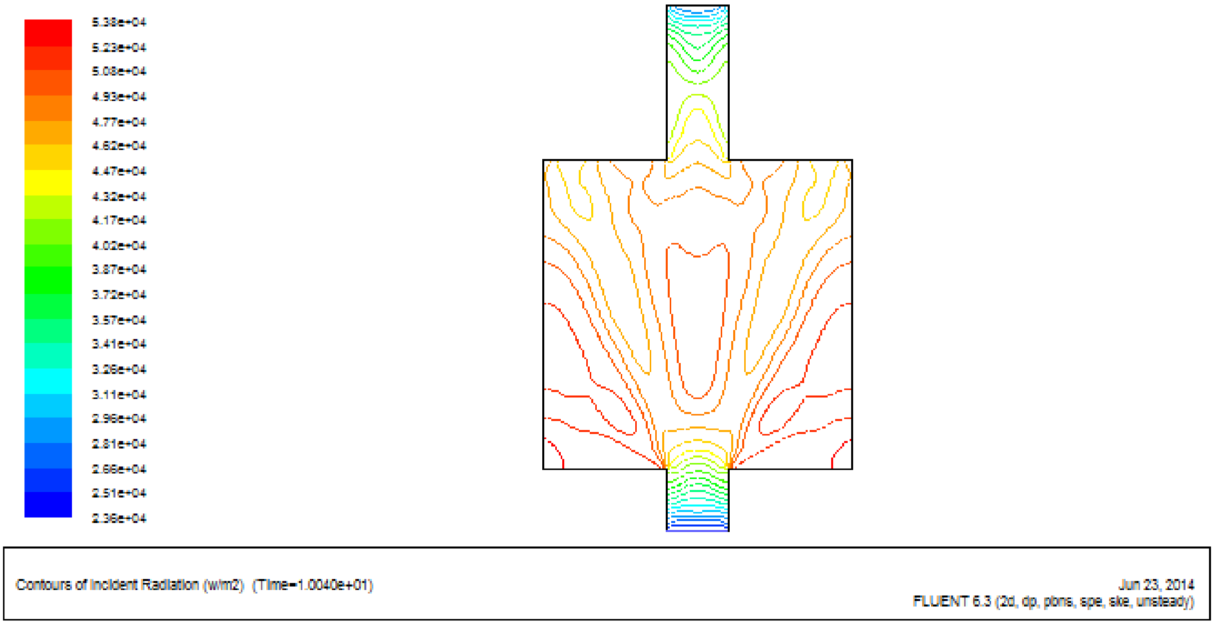

Figure 7: Incident Radiation when Re=10,000

Likewise, we notice that the radiative activity is intense inside the incinerator and all the radiative lines end in the walls where the combustion of smoke components occurs. The maximum values of radiation reach 538 W / m^2 within all the incinerator. The minimal values vary between 296 and 447 W / m^2 and are located at the entry of the system. The Reynolds number Re = 10,000 increased while the intensity of the incident radiation decreased.

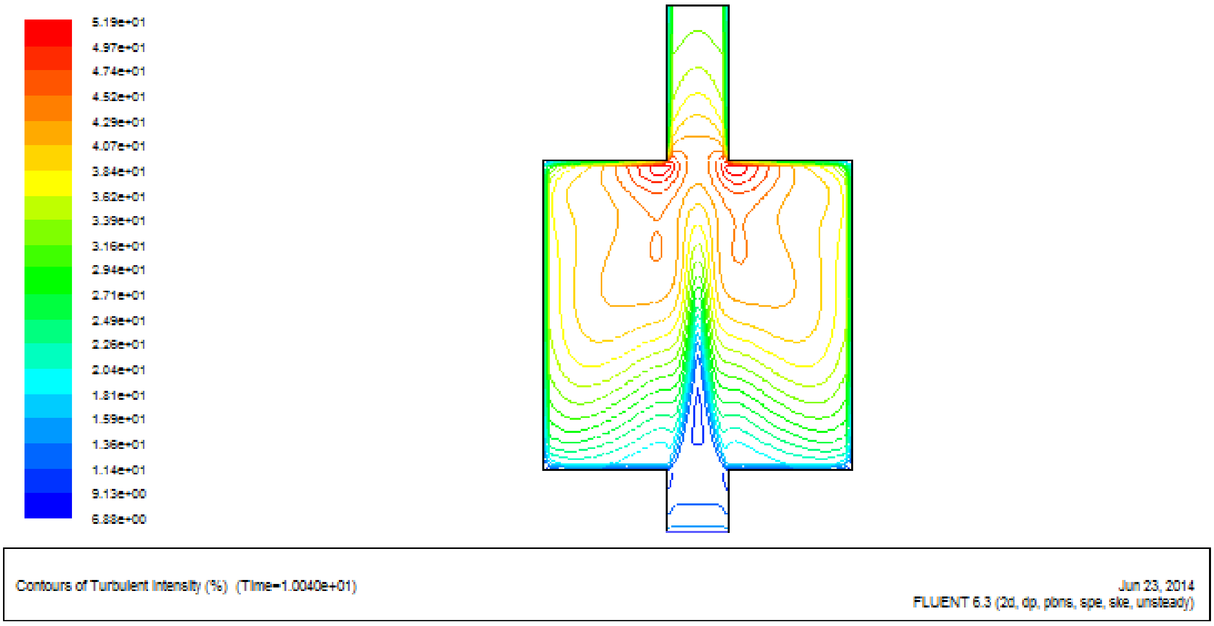

Figure 8: Intensity of the Turbulence when Re=10,000

Turbulence is intense at the upper part of the incinerator and reaches 51.9% while is minimal at the entry, in the chimney, the walls and near the axis of symmetry with values between 15.9% and 40%. This low turbulence in these areas allows a rapid increase in temperature. The Reynolds number increased, but the maximal of the intensity of turbulence decreased.

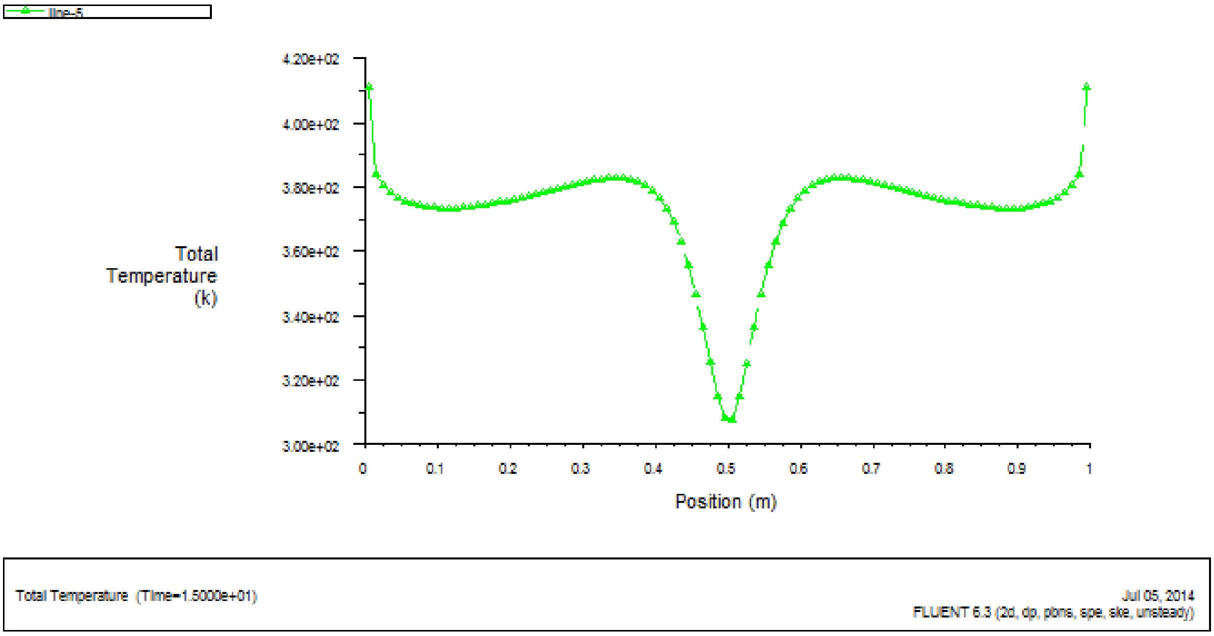

Figure 9: Variation of Temperature at halfway down when Re=10 000

Temperature changes in the halfway down of the incinerator (Figure 9) give maximal values reaching 410 K near the walls where the combustion takes place. The minimal values, around 310 K, are located on the axis of symmetry. Any energy use must be based in the walls for this value of the Reynolds number. With the rise in Reynolds number, the temperatures fall fairly.

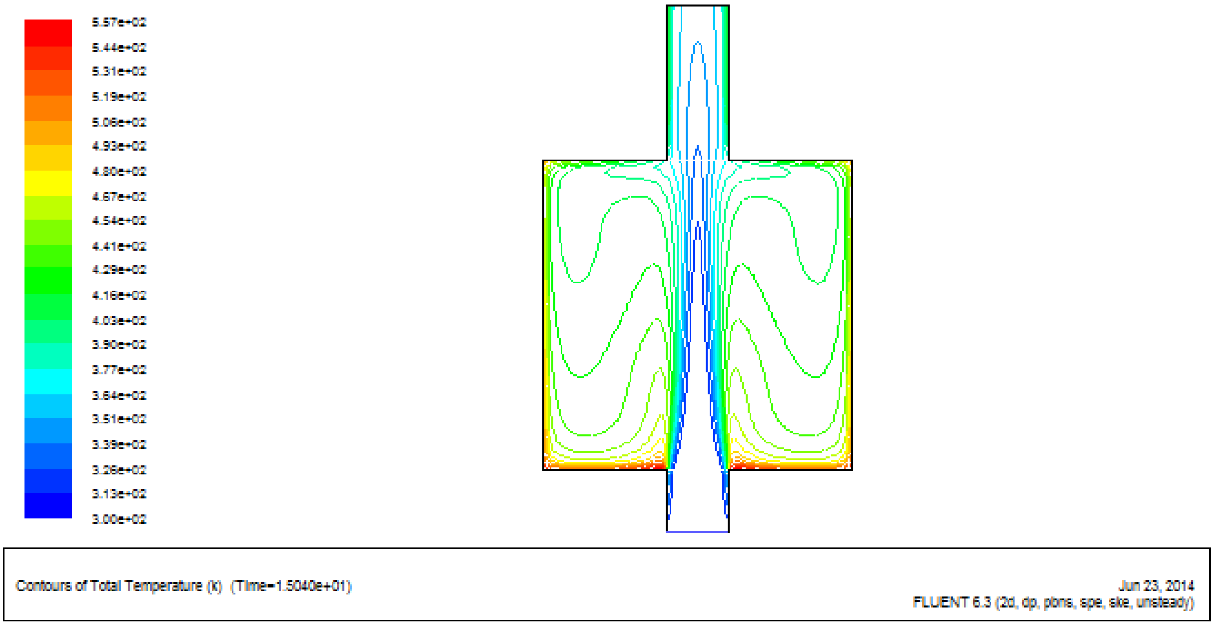

Figure 10: Isotherms with Re=15,000

When the Reynolds number Re = 15 00, the highest temperatures are always found in the walls (up to 557 K horizontal basis walls) while the minimal values are the axis of symmetry (values between 300 and 467 K) (Figure 10).

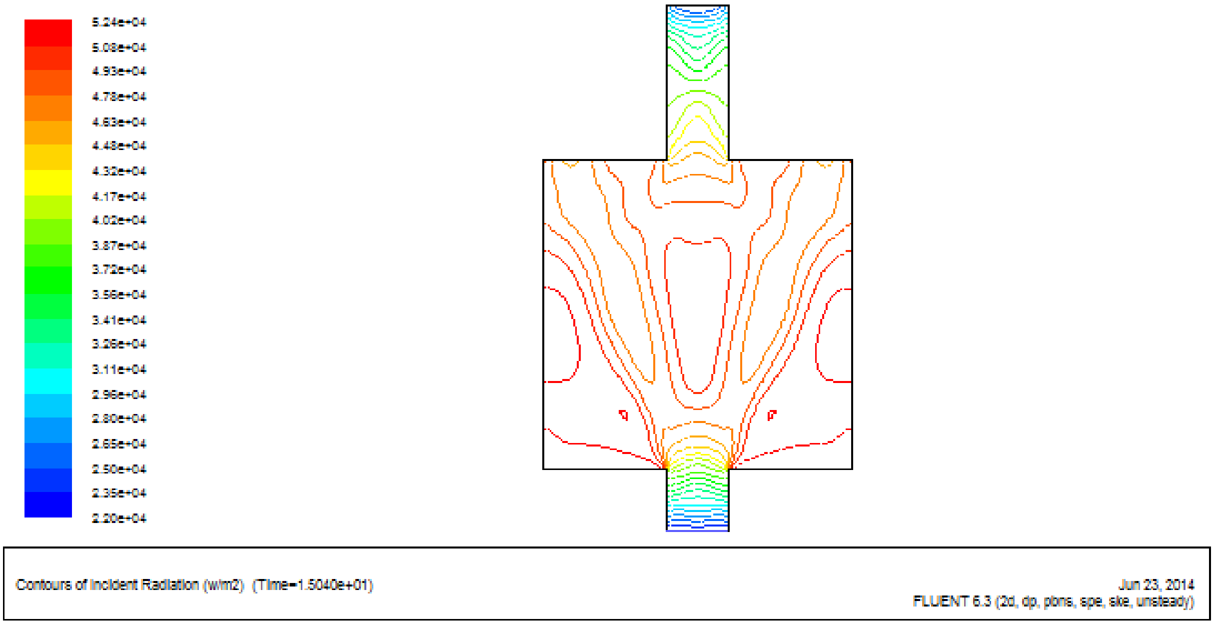

Figure 11: Incident Radiation with Re=15,000

The radiative activity remains intense within the incinerator and all the radiative lines end in the walls where the combustion of smoke components takes place. The maximal values of radiation reach 524 W / m^2 within the incinerator. The minimal values vary between 220 and 417 W / m^2 and are located at the entry to the system. The Reynolds number has increased, Re = 15,000, but the intensity of the incident radiation decreased slightly.

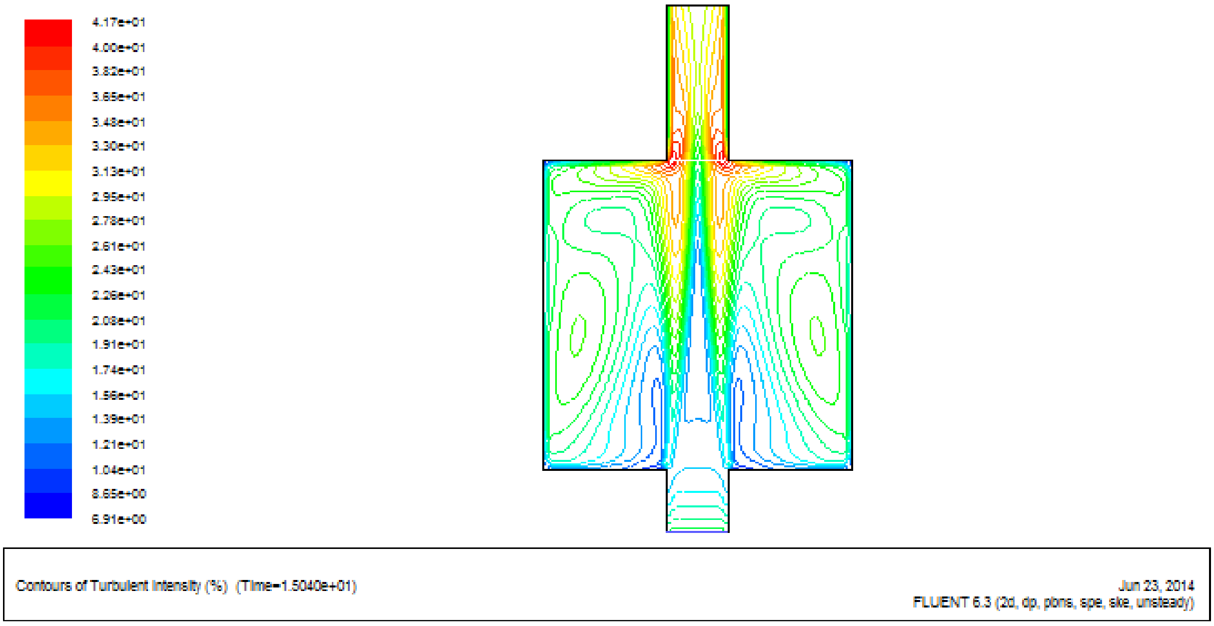

Figure 12: Intensity of the Turbulence with Re=15,000

Turbulence is intense in the upper part of the incinerator and reaches 41.7% and is minimal at the entry of the chimney, in the walls and near the axis of symmetry with values ranging between 6.91% and 31.3%. This low turbulence at these areas allows a rapid increase of temperature thereto. The Reynolds number Re = 15,000 increased while the maximal and minimal values of the intensity of turbulence decreased.

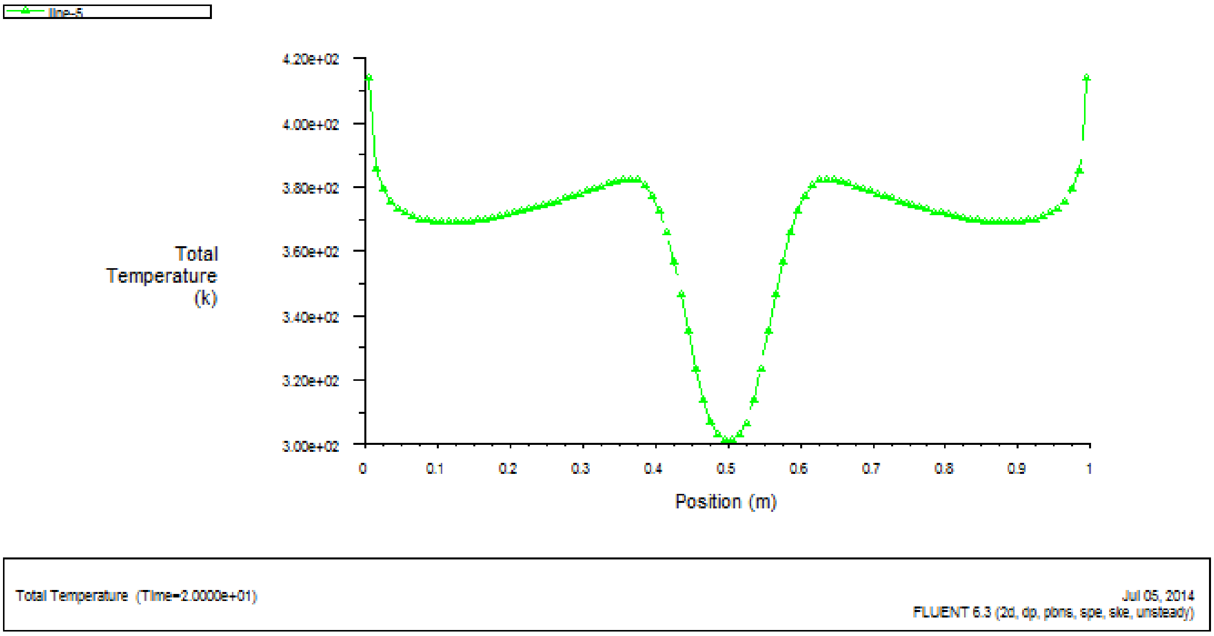

Figure 13: Variation of Temperature at halfway down with Re=15,000

We have marked temperature changes at halfway down of the incinerator. We have found that the maximal values which reach 415 K, are located near the walls where the combustion takes place. The minimal values around 300 K are located on the axis of symmetry (the scope expands) (Figure 13). With the increase of the Reynolds number, temperatures relatively rise near the walls.

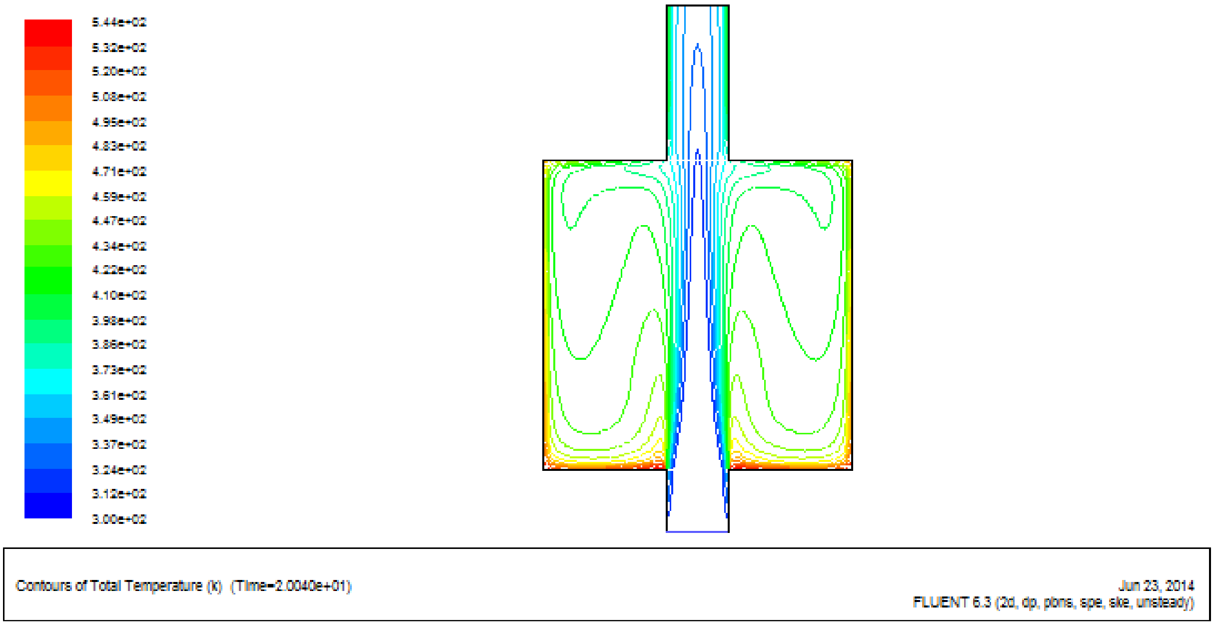

Figure 14: Isotherms with Re= 20,000

The form of isotherms does not change with the increase in the Reynolds number (Re = 20,000), but they get closer to the axis of symmetry. For this value of the Reynolds number, we still have the highest temperatures in the walls (up to 557 K at the horizontal base walls) and the minimal values are around the axis of symmetry (values between 300 and 467 K).

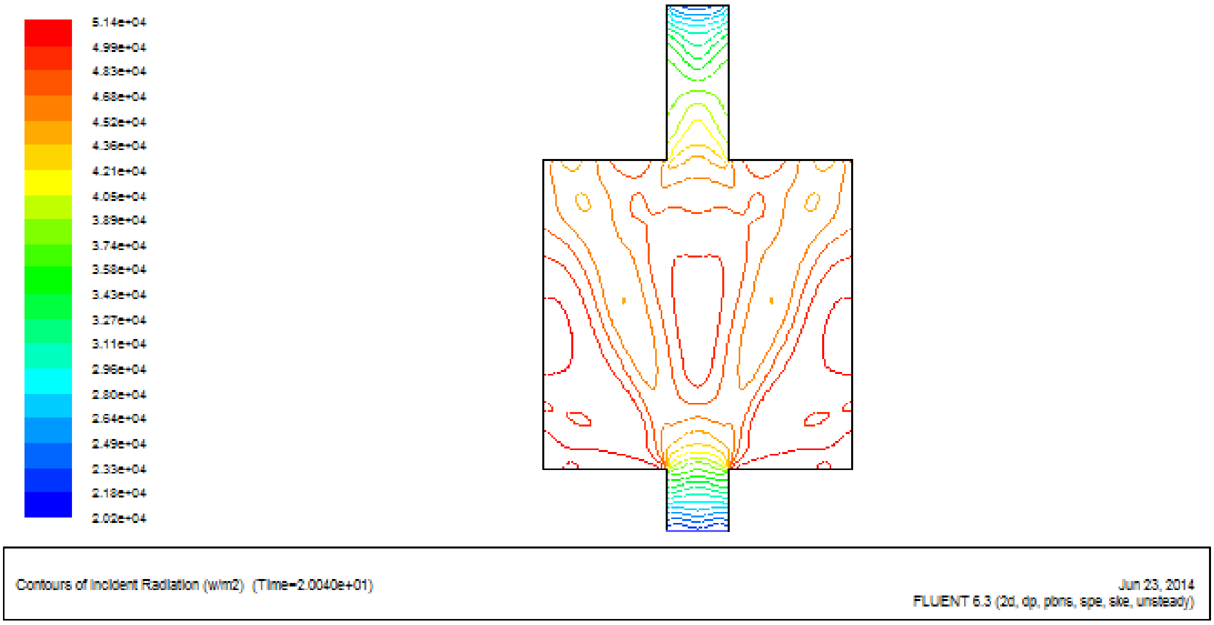

Figure 15: Incident Radiation with Re=20 000

When reconsidering the intensity of the incident radiation (Figure 15) within the incinerator to extend the thermal study of this incineration phenomenon, we notice that radiative activity is intense within the incinerator and all the radiative lines end in the walls where the combustion of smoke components takes place. The maximum values of radiation reach 514 W / m^2 within all the incinerator. The minimal values vary between 202 and 421 W / m^2 and are located within the system. The Reynolds number Re = 20,000 increased and the intensity of the incident radiation decreased slightly.

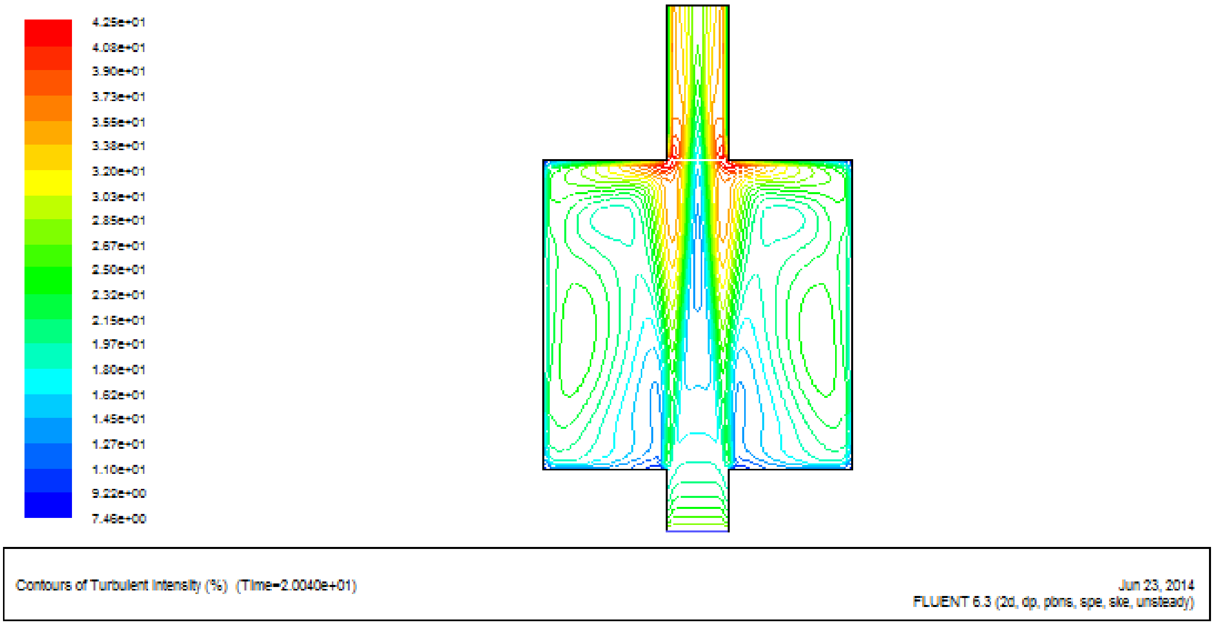

Figure 16: Intensity of the Turbulence with Re=20,000

Turbulence is intense in the upper part of the incinerator and reaches 42.5% and is minimal at the entry of the chimney, in the walls and near the axis of symmetry with values ranging between 7.46% and 32%. This low turbulence at these areas allows a rapid increase of temperature thereto. The Reynolds number increased the same as the maximal and minimal values of the intensity of turbulence (figure 16).

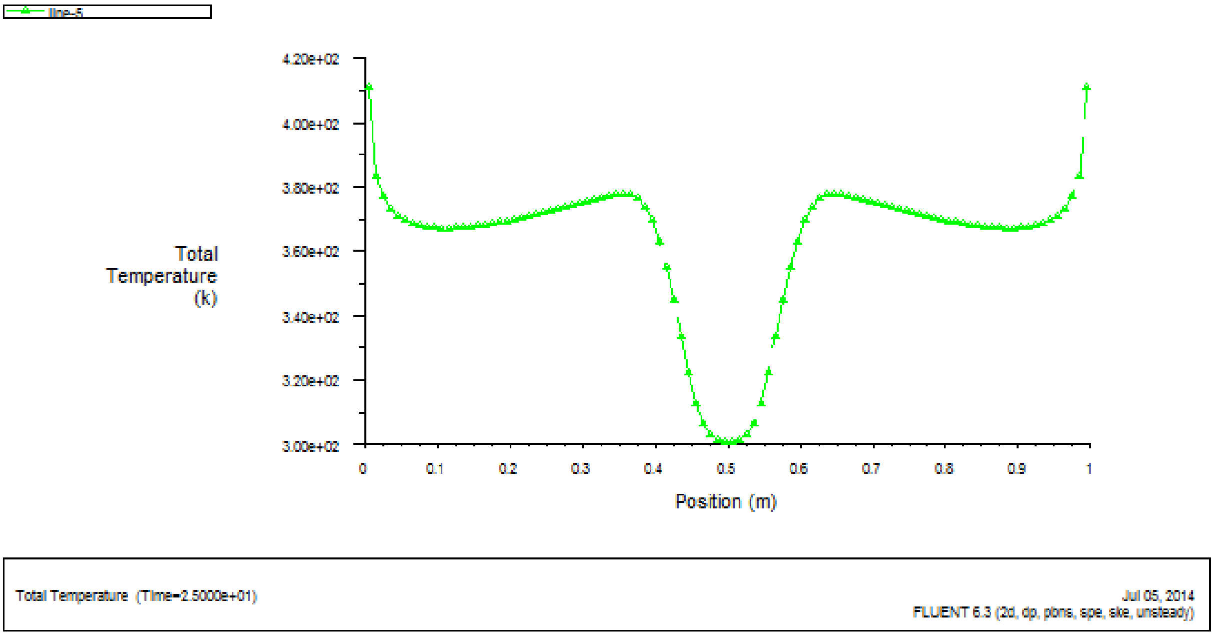

Figure 17: Variation of Temperature at the halfway down when Re=20,000

We have marked temperature changes at halfway down of the incinerator (figure 17). We have found that the maximal values which reach 410 K, are located near the walls where the combustion takes place. The minimal values around 300 K and 360 K, are located on the axis of symmetry (the scope expands). With the increase of the Reynolds number, temperatures relatively rise near the walls.

CONCLUSION

We use FLUENT to solve the incineration smokes generated by the combustion of household wastes in turbulent regime. This is handled with the Navier-Stokes equation, the equation on energy and that on the diffusion of species contained in smokes. The closure model chosen is the standard k-ε for its easy use. Discretization of these equations is using an implicit finite difference method. We use it with a model of overall kinetics and the equation of radiative transfer in the incinerator. The thermal results (isothermal and temperature of the internal walls) of the phenomenon for Reynolds numbers ranging between 5,000 and 20,000 show that combustion takes place near the internal walls where temperatures exceed 600 K.

Furthermore with the increase in the Reynolds number, temperatures fairly increase near the walls. This shows that the thermal use of the system should be done near these walls where we circulate a coolant through coils to recover a significant quantity of heat. Moreover, turbulence is intense in the upper part of the incinerator and reaches 42.5% while it is minimal at the entry, in the chimney, in the walls and near the axis of symmetry with values ranging between 7.46% and 32%, for example, when Re = 20,000. This low turbulence at these areas allows a rapid rise in temperatures in these places. The Reynolds number increased as well as the maximal and minimal values the turbulence intensity.

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