Researches concerning the dynamical flow and the reaction products engendering into a burning installation as variation of the methane gas injected into furnace

Mihai D.L. Țălu and Ştefan D.L. Țălu

***Abstract*—**In the paper there are described the analysis of the dynamic flow and the reaction products engendering as consequence of the methane variation injected through a burner into the furnace. The burning installation has two identical burners. This research work is fulfilled using the FLUENT programme.

***Keywords*—**Burner, methane combustion, Finite Element Method, computational simulation.

I. Introduction

THE burning installation on methane gas have one or more injectors [1].

To establish the field of gas-dynamical flow of methane into a burner it is necessary to solve the transport equations of reactants and products of reaction [2]-[7].

The mechanism of irreversible reaction with complete conversion for methane oxidation reaction is:

$$\underbrace{CH_4 + 2O_2}_{\text{the reactants}} \rightarrow \underbrace{CO_2 + 2H_2O}_{\text{the products of reaction}} \qquad (1)$$

The mathematical model which describes the tensorial form of flow consists by [6]:

- the Reynolds flow turbulent equation (the flame into the industrial installations is designed to be in a turbulent flow regime):

$$\frac{\partial}{\partial t}\left(\bar{\rho}\bar{v}_i\right) + \frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{v}_j\bar{v}_i\right) + \frac{\partial \bar{p}}{\partial x_j} - \bar{\rho}\bar{f}_i + \frac{\partial}{\partial x_j}\left\{\mu_{ef}\left[\left(\frac{\partial \bar{v}_i}{\partial x_j} + \frac{\partial \bar{v}_j}{\partial x_i}\right) - \frac{2}{3}\frac{\partial \bar{v}_i}{\partial x_j}\delta_{ij}\right]\right\} = 0 \qquad (2)$$

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Mihai D.L. Țălu is with the University of Craiova, Romania. He is now with the Department of Applied Mechanics, Faculty of Mechanics, 165 Calea Bucuresti Street, Craiova, 200585 Romania (phone: +40-251-418-803; fax: +40-251-418-803; e-mail: mihai_talu@yahoo.com).

Ştefan D.L. Țălu is with the Technical University of Cluj-Napoca, Romania. He is now with the Department of Descriptive Geometry and Engineering Graphics, Faculty of Mechanics, 103-105 B-dul Muncii Street, Cluj-Napoca, 400641 Romania (e-mail: stefan_ta@yahoo.com).

- the kinetic energy of turbulence:

$$\frac{\partial}{\partial t}\left(\bar{\rho}k\right) + \frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{v}_j k - \frac{\mu_{ef}}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + c\bar{\rho}\varepsilon - \frac{\partial v_i}{\partial x_j}\left\{\mu_{ef}\left[\left(\frac{\partial \bar{v}_i}{\partial x_j} + \frac{\partial \bar{v}_j}{\partial x_i}\right) - \frac{2}{3}k\delta_{ij}\right]\right\} = 0 \qquad (3)$$

- the mass continuity equation:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{\rho}\bar{v}_j\right) = 0 \qquad (4)$$

- the transport equations for reactants CH_4 and O_2:

$$\frac{\partial}{\partial t}\left(\bar{\rho}\cdot m_{CH4}\right) + \nabla\cdot\left(\bar{\rho}\cdot\vec{v}\cdot m_{CH4}\right) - \nabla\cdot\left(\bar{\rho}\cdot Dm_{CH4}\right) = S_{CH4} \qquad (5)$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\cdot m_{O_2}\right) + \nabla\cdot\left(\bar{\rho}\cdot\vec{v}\cdot m_{O_2}\right) - \nabla\cdot\left(\bar{\rho}\cdot Dm_{O_2}\right) = S_{O_2} \qquad (6)$$

- the transport equations for products of reaction CO_2, H_2O, N_2:

$$\frac{\partial}{\partial t}\left(\bar{\rho}\cdot m_{CO_2}\right) + \nabla\cdot\left(\bar{\rho}\cdot\vec{v}\cdot m_{CO_2}\right) - \nabla\cdot\left(\bar{\rho}\cdot Dm_{CO_2}\right) = S_{CO_2} \qquad (7)$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\cdot m_{H_2O}\right) + \nabla\cdot\left(\bar{\rho}\cdot\vec{v}\cdot m_{H_2O}\right) - \nabla\cdot\left(\bar{\rho}\cdot Dm_{H_2O}\right) = S_{H_2O} \qquad (8)$$

$$\frac{\partial}{\partial t}\left(\bar{\rho}\cdot m_{N_2}\right) + \nabla\cdot\left(\bar{\rho}\cdot\vec{v}\cdot m_{N_2}\right) - \nabla\cdot\left(\bar{\rho}\cdot Dm_{H_2}\right) = S_{N_2} \qquad (9)$$

This paper presents the partial results of the 3D distribution fields concerning the dynamic flow fields of pressure, density, temperature, velocity and the distribution mass fraction for the products of reaction: CH_4, CO_2, O_2, H_2O and N_2 emitted into a burning chamber with two identical methane burner, Fig. 2, as result of the heat density variation of one of them (Br1).

The main constructive sizes of burning installation are given in Table I [8].

Table I. The main constructive sizes of burning installation.

r_1	R_1	r_2	R_2	l_c	L	$l_1 = l_2 = 2.2$ (2R)	α
[mm]							[°]
3	10	12	30	18	4500	110	7.5

The burner's scheme and their 3D assembling on installation are shown in Fig. 1 and Fig. 2.

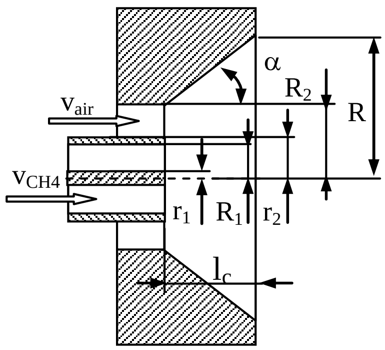

Fig. 1. The burner's scheme.

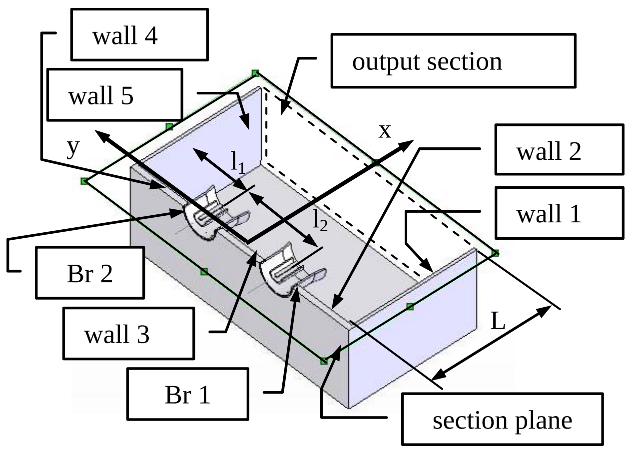

Fig. 2. The burning installation.

The coefficient of air excess is $\lambda = 1.1$ and the temperatures $T_{CH4} = T_{air} = 300$ [K]; the output of burner is connected to atmosphere. The flow volumes of feeding the burners are given in Table II.

II. THE ANALYSIS WITH THE F.E.M.

The F.E.M. analysis and the modeling of the burning chamber is made using the Fluent 6.2.16 and Gambit 2.2.30 programmes. The partial results of analysis concerning the 3D fields of the dynamic flow in the plane with maximum heat density which passing through the burners axes, Fig. 2 and into 3D domain of flow are presented.

The changing of the heat density of burner Br1 (through variations of CH_4 which is injected into furnace) demanded a separately study of flow fields in the interior domain of flow and on the frontiers: walls of burning chamber and on the output section, Fig. 2.

The study cases are given in Table II [8].

Table II. The study cases.

	Case	Q_{CH4}	Q_{air}		Case	Q_{CH4}	Q_{air}
		[m^3/h]				[m^3/h]	
Br1	C1	0	0		C7	9.26	103.98
	C2	4.11	47.55		C8	10.29	118.87
	C3	5.14	59.43		C9	11.32	130.75
	C4	6.17	71.32		C10	12.35	142.65
	C5	7.20	83.21	Br2	C6	8.23	95.10
	C6	8.23	95.10				

The numerical results of simulation into volume domain of flow are given in Table III and for the temperature on the frontiers in Table IV.

Table III. The numerical results of simulation into volume domain of flow.

Physical sizes	Integral volume average of sizes			
	Case			
	C1	C2	C3	C4
p[Pa]	0.0074	1.148	1.57623	2.00155
ρ[kg/m^2]	0.17541	0.1809	0.18192	0.18283
T[K]	1908.39	1865.8	1857.05	1849.03
v[m/s]	7.26	10.76	11.6066	12.4443
CH_4	0.0696	0.0789	0.08025	0.08061
CO_2	0.13211	0.13056	0.12970	0.12889
O_2	0.01079	0.01084	0.01205	0.01321
N_2	0.679	0.67195	0.67180	0.67175
H_2O	0.10815	0.10689	0.10618	0.10552
	C5	C6	C7	C8
p[Pa]	2.39350	2.78311	3.12201	3.44071
ρ[kg/m^2]	0.18343	0.18370	0.18371	0.18350
T[K]	1843.75	1841.62	1842.11	1844.48
v[m/s]	13.2943	14.1631	15.0500	15.9558
CH_4	0.08083	0.08087	0.08076	0.08058
CO_2	0.12835	0.12809	0.12806	0.12819
O_2	0.01399	0.01438	0.01446	0.01429
N_2	0.67172	0.67176	0.67186	0.67196
H_2O	0.10508	0.10487	0.10484	0.10495
	C9	C10		
p[Pa]	3.69408	3.93328		
ρ[kg/m^2]	0.18317	0.18281		
T[K]	1847.97	1851.74		
v[m/s]	16.8730	17.7925		
CH_4	0.08033	0.08001		
CO_2	0.12843	0.12869		
O_2	0.01398	0.01366		
N_2	0.67209	0.67226		
H_2O	0.10515	0.10536		

Considering as reference the values from case C6, in Fig. 3 the abscissae represents the percentage of effective methane flow volume injected in burner Br1 (Q_{1ef}) and on the ordinate the percentage of the variation for the physical sizes from cases C1 to C10 [9].

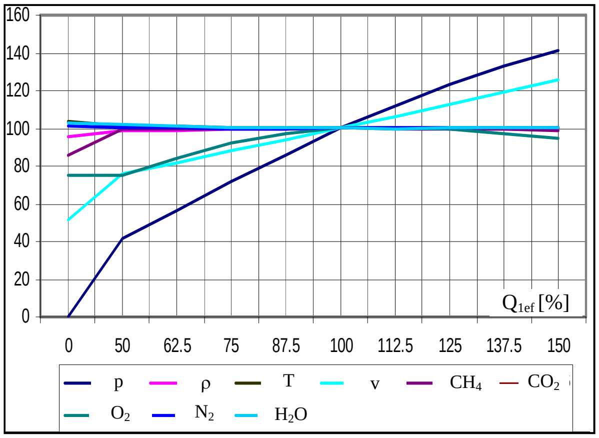

Fig. 3. The percentage of the variation for the physical sizes from cases C1 to C10 in function of Q_{1ef}.

Table IV. The numerical results of simulation for the temperature on the frontiers.

Case		T[K]	
		Medium value	Maximum value
C1	wall 1	2150.50	2292.60
	wall 2	1713.20	1738.80
	wall 3	1414.80	1535.00
	wall 4	1367.65	1445.00
	wall 5	2093.85	2308.60
	output section	1921.25	2245.80
C2	wall 1	2151.15	2303.90
	wall 2	1340.80	1457.00
	wall 3	878.53	1010.90
	wall 4	1498.30	1589.40
	wall 5	2198.75	2313.95
	output section	1912	2191.56
C3	wall 1	2166.00	2305.30
	wall 2	1324.70	1437.20
	wall 3	816.44	929.70
	wall 4	1521.16	1614.85
	wall 5	2204.36	2314.74
	output section	1913.67	2173.87
C4	wall 1	2168.31	2305.50
	wall 2	1311.60	1421.30
	wall 3	780.76	882.86
	wall 4	1540.16	1636.16
	wall 5	2205.52	2315.30
	output section	1916.54	2186.15
C5	wall 1	2162.02	2305.75
	wall 2	1300.47	1407.85
	wall 3	761.42	857.70
	wall 4	1557.00	1655
	wall 5	2204.01	2315.72
	output section	1916.85	2201.27
C6	wall 1	2150.90	2305.60
	wall 2	1289.52	1394.70
	wall 3	755.84	850.02
	wall 4	1571.11	1671.44
	wall 5	2150.90	2305.60
	output section	1918.73	2209.07
C7	wall 1	2136.46	2305.36
	wall 2	1279.59	1382.96
	wall 3	759.16	853.98
	wall 4	1584.01	1685.88
	wall 5	2196.36	2315.81
	output section	1919.03	2213.74
C8	wall 1	2120.97	2305
	wall 2	1270.75	1372.6
	wall 3	768.70	866
	wall 4	1596.10	1698.9
	wall 5	2191.04	2315.35
	output section	1920.81	2230.10
C9	wall 1	2105.56	2304.60
	wall 2	1262.84	1363.40
	wall 3	784.18	885.70
	wall 4	1606.33	1710.50
	wall 5	2185.33	2314.50
	output section	1920.93	2242.75
C10	wall 1	2090.40	2304.15
	wall 2	1255.65	1355.05
	wall 3	802.84	909.70
	wall 4	1615.76	1721.25
	wall 5	2179.65	2312.90
	output section	1921.27	2251.60

From Fig. 4 to Fig. 11 as exemplification are given the distributions fields of the dynamical flow for sizes from Table III corresponding to the case C2.

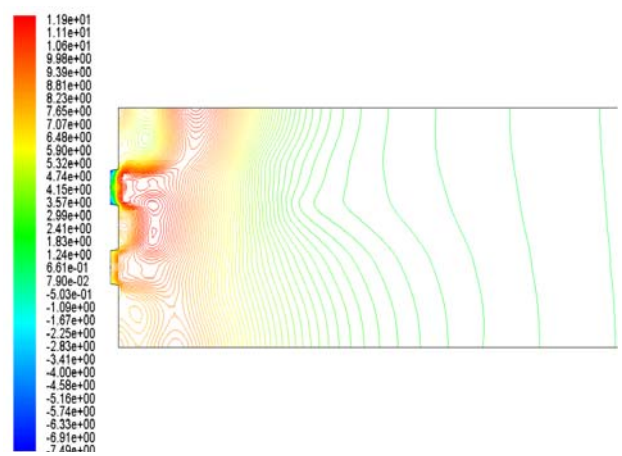

Fig. 4. The pressure.

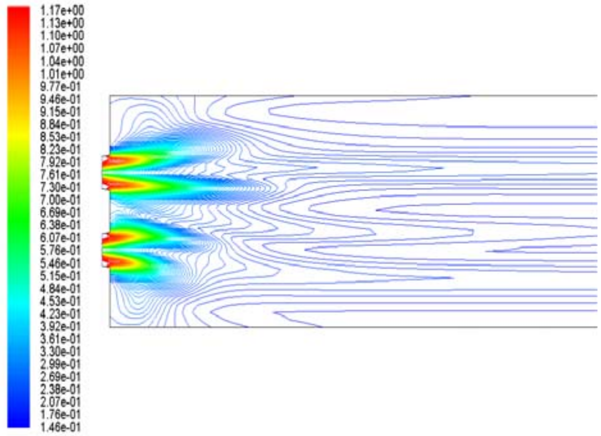

Fig. 5. The density.

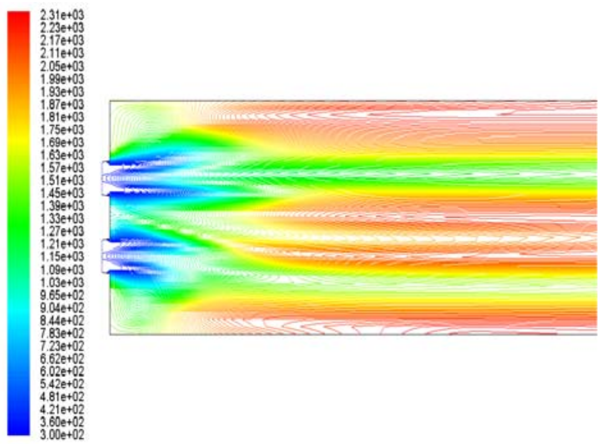

Fig. 6. The temperature.

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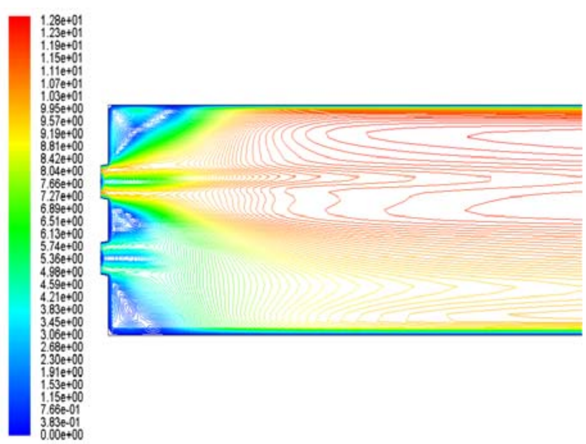


Fig. 7. The velocity.

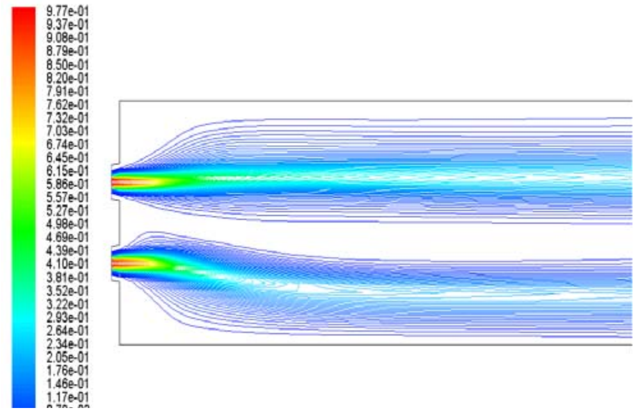


Fig. 8. The mass fraction of CH_4.

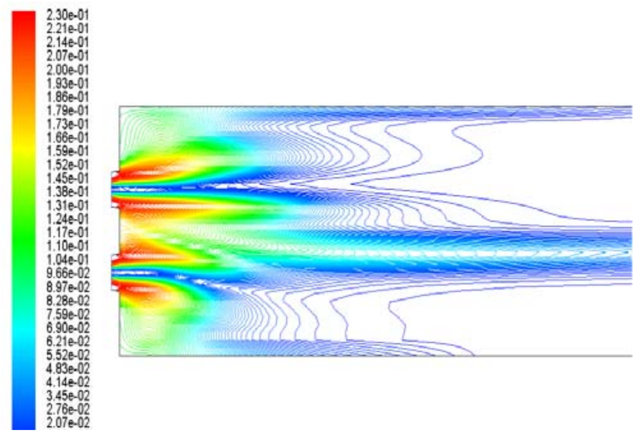


Fig. 9. The mass fraction of O_2.

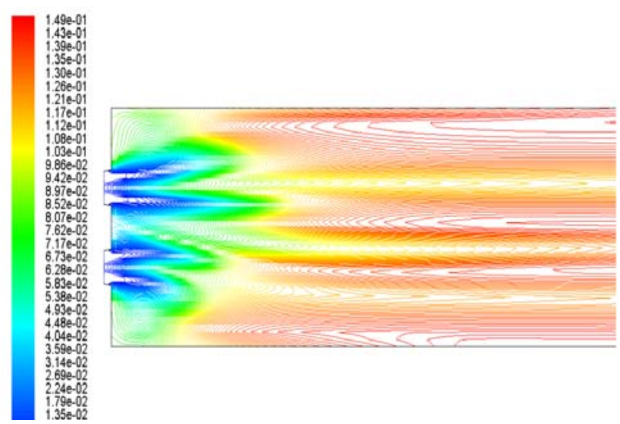


Fig. 10. The mass fraction of CO_2.

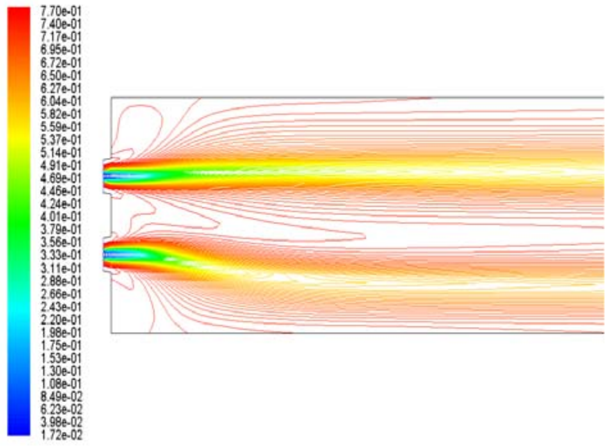


Fig. 11. The mass fraction of N_2.

The temperature fields in section plane with maximum heat density for cases C1, C4, C8 and C10 are shown in Fig. 12 to Fig. 15. The medium value and the maximum value of temperature on domain frontiers are given in Table IV.

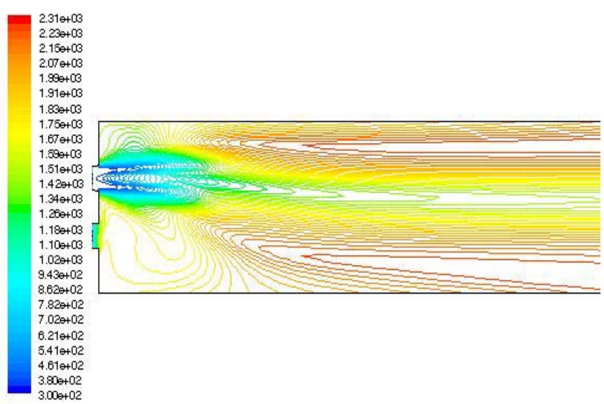


Fig. 12. The temperature fields in section plane with maximum heat density for case C1.

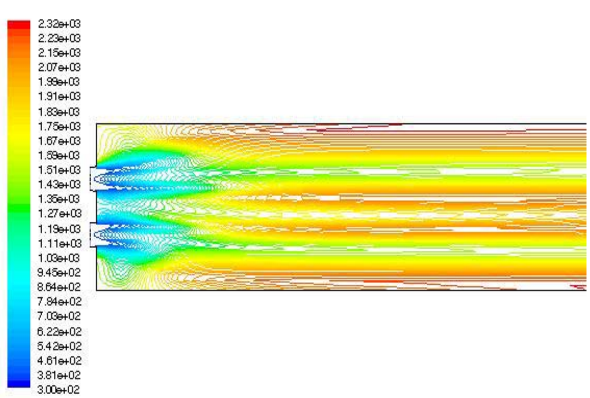


Fig. 13. The temperature fields in section plane with maximum heat density for case C4.

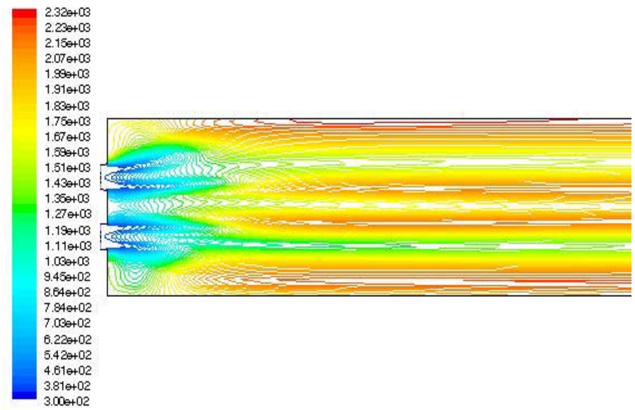


Fig. 14. The temperature fields in section plane with maximum heat density for case C8.

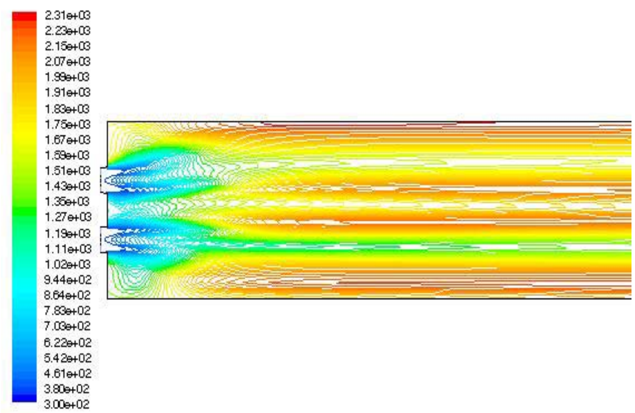


Fig. 15. The temperature fields in section plane with maximum heat density for case C10.

The numerical results of simulation for $|\Delta T_{max}|$ are given in Table V and for the deviations of sizes in [%] in Table VI.

Table V. The numerical results of simulation for $|\Delta T_{max}|$.

	$\|\Delta T_{max}\|$
wall 1	0.25
wall 2	7.20
wall 3	28.0
wall 4	10.0
wall 5	0.08
output section	3.50

Table VI. The numerical results of simulation for the deviations of sizes in [%].

Physical sizes	Deviations of sizes in [%]		
p[Pa]	↗ 100 %	P_{NW} $[Q_N, T_N]$	↗ 41.3 %
ρ[kg/m²]	↗ 4.52 %		↘ 0.5%
T[K]	↘ 3.62 %		↗ 0.55 %

v[m/s]	↗ 48.75 %		↗ 25.62 %
CH_4	↗ 14 %		↘ 1.1%
CO_2	↘ 3.14 %		↗ 0.47 %
O_2	↗ 25 %		↘ 5%
N_2	↘ 1 %		↗ 0.07 %
H_2O	↘ 3.12 %		↗ 0.5 %

To make the study of the temperature variation as consequence of the flow methane volume injected in burner Br1, is take as reference the correspondent sizes of the nominal regime of work, (case C6).

The plots have the values of physical sizes in percentage. Abscissae is the flow volume of methane injected in burner Br1 and the ordinate is the effective temperature. Considering the values from Table II and Table IV were traced using Maple 11 programme the variation of medium values in Fig. 16 and maximum values in Fig. 17 and Fig. 18.

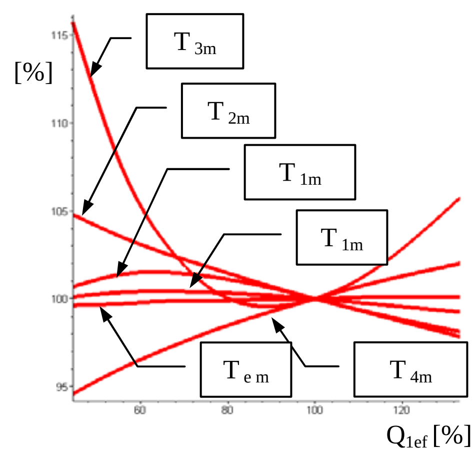
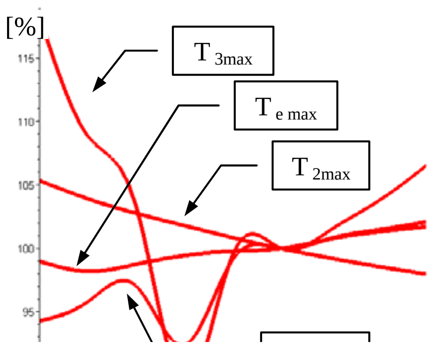


Fig. 16. The percentage of the variation for the medium temperature in function of Q_{1ef}.



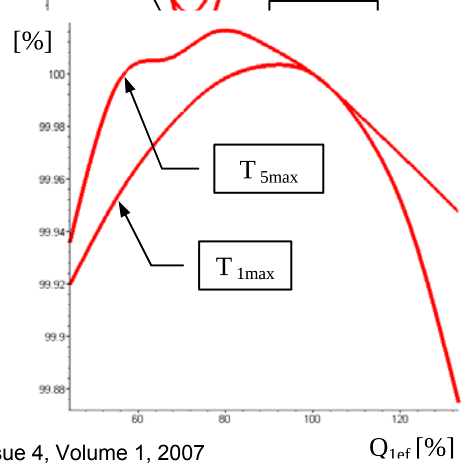


Fig. 17. The percentage of the variation for the maximum temperature of: T_2, T_3, T_4, T_e in function of Q_{1ef}.

Fig. 18. The percentage of the variation for the maximum temperature of: T_1, T_5 in function of Q_{1ef}

III. CONCLUSIONS

The analysis with the Finite Element Method provides the turbulent flow regime with the internal and external recirculation zones, for fuel mixture injected into furnace and for the emitted gases resulted from the oxidation reaction of methane (Fig. 6).

With increasing the flow volume of methane injected, the maximum values of temperature field increases and moving to output section (Fig. 13 to Fig. 16).

Analyzing from Table IV the values of the modulus deviation for the maximum temperature, given in table VI, we can make the following remark:

- the bigger deviation of temperature in order, is on the frontal walls (the wall with 3, respective 28 %), the next on the output sections 3, with 5 % and the last on lateral the walls, (the wall 1, with 0.25 %).

In Table VI are given the percentage deviations in relation with the point of the nominal regime calculated as integral volume average into 3D domain of flow starting to values from Table III.

The p, v, O_2 and CH_4 have height deviations considering as reference their values from nominal point of work P_{NW} [Q_N,T_N] and in opposition side the physical sizes ρ, T, CO_2, N_2 and H_2O have small deviations under $\Delta < 4.5$ %.

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Mihai D.L. Țălu was born in Florești, county Vaslui, Romania, on November 5, 1962. He graduated as a mechanical engineer from University of Craiova, Faculty of Mechanics, Romania in 1987. He received his Ph.D. degree in technical sciences with specialty in mechanical engineering, on 2000 from the University of Craiova, Romania.

From 1990 to 2001, he was Assistant Professor in Department of Applied Mechanics, Faculty of Mechanics, University of Craiova, Romania. From 2001 at present, he is Lecturer in Department of Applied Mechanics, Faculty of Mechanics, University of Craiova, Romania. He has published 10 books and 93 scientific papers in international journals, national and international conferences. His research interests include applied mechanics, mechanics of fluids, the finite element method, multiobjective optimization, numerical calculus, applied statistics, thermotechnics and computer simulation.

Dr. Mihai has been involved in numerous research projects led at the Technical University of Craiova, Romania and some scientific grants with the Romanian Ministry of Education, Research and Youth, through The National University Research Council. Currently he is a member of the Romanian Society of Theoretical and Applied Mechanics.

Ștefan D.L. Țălu was born in Florești, county Vaslui, Romania, on July 31, 1964. He graduated as a mechanical engineer from University of Craiova, Faculty of Mechanics, Romania in 1988. He received his Ph.D. degree in technical sciences with specialty in technology of machine building, on 1998 from the Technical University of Cluj-Napoca, Romania.

From 1991 to present, he worked in Department of Descriptive Geometry and Computer Graphics, Faculty of Mechanics, Technical University of Cluj-Napoca, Romania. He is currently Associate Professor in Department of Descriptive Geometry and Computer Graphics, Faculty of Mechanics, Technical University of Cluj-Napoca, Romania. He has published 13 books and 142 scientific papers in international journals, national and international conferences. His research interests include descriptive geometry, technical drawing, mathematical algorithms for solving the optimum problems, technology of machine building and computer aided design.

Dr. Ștefan has been involved in numerous research projects led at the Technical University of Cluj-Napoca, Romania and some scientific grants with the Romanian Ministry of Education, Research and Youth, through The National University Research Council. Currently he is a member of the Romanian Association of Engineering Graphics, member of the General Association of Romanian Engineers as well as member of the Romanian Committee for the History and Philosophy of Science and Technology of Cluj territorial branch of the Romanian Academy.