Numerical validation of viewFactor and FVDOM radiation models of OpenFOAM® and application in the study of food furnaces

Validación numérica de los modelos de radiación viewFactor y FVDOM en lo OpenFOAM® y aplicación en lo estudio de los hornos alimenticios

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ABSTRACT

Continuous tunnel furnace has greater flexibility in heating and high productivity and it was becoming the best option for processing industrialized food products. The main objective of this work is the validation of the results from radiation models viewFactor and FVDOM. In his case, the software OpenFOAM® was used and one of its applications in the evaluation of net rate heat exchanges by radiation on the mat of a real continuous furnace. The geometry, operational conditions, mesh definition, initial and boundary conditions used in the model were obtained from literature data, technical manuals and operational furnaces found in food industries. The implementation and simulation of physical model, in the OpenFOAM® has several simplifying hypothesis highlighting air is treated as an ideal and incompressible, Newtonian and non-participant to the exchanges of heat by radiation; laminar flow viewFactor and FVDOM radiation models; pressure-velocity coupling algorithm SIMPLE. The results obtained were used to validate the radiation models through analytical results and also the convective heat flux. The orders of magnitude between radiation and convection turn it difficult to correctly evaluate the heat flux. Small fluctuations in temperature and velocity affect considerably and induce oscillations on the heat flux results. The viewFactor radiation model was more advantageous due to its greater simplicity and higher convergence velocity.

Keywords: Radiation model, food furnace, OpenFOAM®.

RESUMEN

Los hornos continuos del tipo túnel, considerando su mayor flexibilidad en el calentamiento y su alta productividad, se transformaron en la mejor opción para el procesamiento de productos alimenticios industrializados. Los objetivos principales de este trabajo son la validación de los resultados de los modelos de radiación viewFactor y FVDOM del software OpenFOAM® y aplicación en la evaluación de las tasas de transferencia de calor por la radiación sobre la estera de un horno continuo alimenticio real. La geometría, condiciones operacionales, definiciones de la malla y condiciones iniciales y de contorno utilizados en la construcción del modelo fueron obtenidos a partir de datos de la literatura, manuales técnicos y hornos operacionales encontrados en las industrias alimenticias. En la construcción del modelo físico, implementación y simulación en el OpenFOAM®, diversas hipótesis simplificadoras fueron levantadas – el aire como un gas ideal, incompresible, newtoniano y no participante a los cambios radiantes; vaciamiento laminar; utilización de las ecuaciones de la continuidad, del balance de los momentos, de la energía y los modelos de radiación viewFactor y FVDOM; algoritmo del acoplamiento

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presión-velocidad SIMPLE, etc. De los resultados obtenidos, se destacan la validación de los modelos de radiación a través de resultados analíticos y también el flujo de calor por convección sobre la estera poco significativo en comparación a los efectos de la radiación. La discrepancia entre las órdenes de grandeza de la radiación y convección hace difícil la correcta evaluación de la última, especialmente porque pequeñas oscilaciones en la temperatura y velocidad afectan considerablemente e inducen a oscilaciones en su comportamiento. El modelo de radiación viewFactor se mostró más ventajoso debido a su mayor simplicidad y mayor velocidad de convergencia de la solución.

Palabras clave: Modelos de radiación, hornos alimenticios, OpenFOAM®.

INTRODUCTION

Thermal radiation is the form of energy emitted by matter. Any substance at an absolute nonzero temperature emits electromagnetic waves or photons on thermal radiation range. The heat exchange does not require a material medium to occur, being more efficient in a vacuum. It is comprised in the wavelength range 0.1 to 100 μm, covering the infrared, visible and part of the ultraviolet spectrum. Radiation can be treated volumetric phenomenon and as a surface phenomenon for emissions from 1 μm of the exposed surface. This heat transfer mode is very relevant in studies of industrial processes of heating, cooling, drying, combustion, solar radiation and others. [1-2].

A furnace is designed considering all forms of heat transfer – conduction, convection and radiation. Even with the most modern design changes and optimizations for better utilization of the convection, the radiation continues being the most important and preponderant form. Its rate varies with temperature - proportional to the fourth power, according to Stefan-Boltzmann's Law – and with the average absorption of the products to be cooked, which are a function of some factors such as form, color and surface finishing [3-4].

Through a CFD model for a furnace of heating electric in domestic scale, [5] compared and concluded that the radiation models viewFactor (Surface to Surface – S2S), DTRM (Discrete Transfer Radiation Model) and DOM (Discrete Ordinates Method) or FVDOM (Finite Volume Discrete Ordinates Method) have the same results. The last model was considered more advantageous for the possibility of inclusion of participating media in heat exchanges by radiation and between surfaces; also to include the solution between semitransparent walls.

In [6] it was highlighted the use of the FVDOM radiation model in the food industry, specifically in the process of cooking breads in a pilot-scale electric oven. Considering the mechanisms of water evaporation and condensation inside the bread and the influence of the load of the furnace (partially and completely loaded) it was developed and validated a CFD 3D model for the study of temperature profiles and air velocities inside the furnace. The authors used in their work the softwares GAMBIT®, for geometry construction and mesh definition and ANSYS FLUENT®, for solving the governing equations and initial and boundary conditions.

It was also developed by [7], a method for radiation analysis and simultaneous temperature measurements coupled to the medium absorption coefficients, and emissivity of the walls in tunnel type furnaces oil-fired. The method is based on the Equation of Radiative Transfer (RTE) and develops a radiation image model. The image inversion provides the distributions of temperatures and the radiative properties of the medium and the walls. The validation and viability verification of the method occurred through numerical analysis and with experimental results obtained from measurements using thermocouples. The results obtained can be used in the analysis of the performance of the burner, the heat exchanges inside the furnace and the radiative properties of the medium and the walls. This procedure can be extremely important in combustion studies.

The modeling and numerical solution of convective and radiative heat transfers, combined, inside a square cavity with a participant media and isotropic were presented by [8]. The presented work shows the application of the Method of Discrete Ordinates in the solution of RTE. Results from the numerical model are compared with others available in the literature.

The free and open source software OpenFOAM® (*Open Field Operation and Manipulation*) was originally developed as a set of C ++ libraries, aimed at analyzing and manipulating tensorial fields in Fluid Dynamics and quickly became very popular either in the industrial area as in academic research. Their choice can be justified by several aspects like: a) No limitations on parallel computing. b) The possibility of total understanding of the code (without the presence of "black boxes", as in most famous commercial software) and with numerous possibilities of modifications, according to the needs and particularities of the problem situation. c) Free tools for mesh generation (blockMesh and snappyHexMesh) and data visualization, incorporated into the package (ParaView). d) Multiplataform (Linux®, MacOS®, Windows®, etc.). e) An extensive list of numerical discretization schemes and mathematical models implanted – which offers robustness and efficiency in the wide modeling of Computational Fluid Dynamics, etc. [9].

The main objective of this work is to validate the radiation models viewFactor and FVDOM of the software OpenFOAM® using a problem situation with an evacuated cavity having constant and known wall temperatures. Then apply these models in the evaluation of heat transfer by radiation and convection on the oven mat of a continuous food furnace using real dimensions and operational conditions. The quality of the results achieved was analyzed discussing the most efficient model to be used in the evaluated situation.

PHYSICAL MODEL

Furn Furnace Geometry

Figures 1, 2 and 3 illustrate the schematic drawings of the three-dimensional furnace studied. The furnace has square cross section geometry with sides of 1 m and a longitudinal length of 5 m. A burner tube of diameter 0.283 m is located in the upper central region of the furnace. The furnace dimensions and operational conditions used in this work were established according to commercial standards of furnaces, data found in the literature and technical manuals.

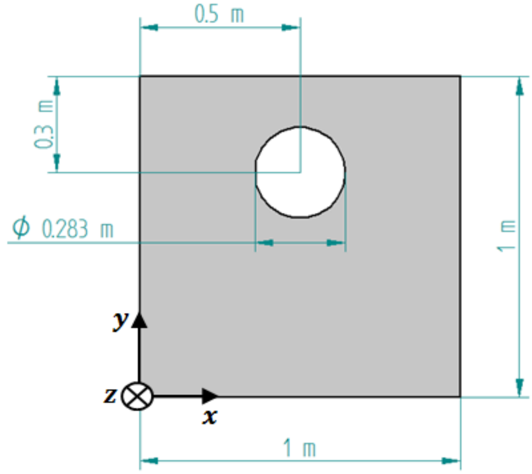

Figure 1. Schematic drawing of furnace – front view.

Figure 2. Schematic drawing of furnace – lateral view.

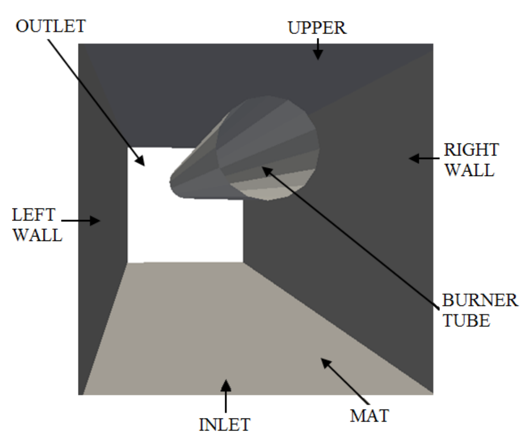

Figure 3. Schematic drawing of furnace-isometric view.

Figure 3 shows the physical furnace model with the burner tube and the established names for walls and different regions. These designations are defined as follow and they were introduced in order to set the initial and boundary conditions in the furnace simulation problem.

- Inlet ($z = 0$) and Outlet ($z = 5$) – No restrictions on the airflow from the inside the furnace and representative of large losses of energy.
- Burner Tube – Longitudinal tube located in the upper central region of the furnace, with uniform surface temperature equal to 300ºC.
- Letf Wall ($x = 0$), Right Wall ($x = 1$) and Upper ($y = 1$) – Side walls and upper surface of the furnace, admitted as adiabatics.
- Mat ($y = 0$) – the longitudinal movement of the products to be cooked with a constant velocity of 0.1 m/s.

Similar boundary conditions characterize these regions and are defined as patches in the simulation and programming.

Governing Equations

In the selection of the governing equations and definition of the mathematical model to be solved, several simplifying hypotheses and physical models were adopted. Based on the problem physics and typical conditions established in [10] and [11], the following conditions and equations were used:

$$p = \rho R T \tag{1}$$

$$\tilde{U} = C_\upsilon T \tag{2}$$

$$\nabla . \mathbf{u} = 0 \tag{3}$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{g}\left(1 - \beta\left(T - \overline{T}\right)\right) \tag{4}$$

$$\rho C_\upsilon \frac{DT}{Dt} = -\nabla . \mathbf{q} - p(\nabla . \mathbf{u}) \tag{5}$$

, where p is the static pressure, ρ specific mass, R gas constant, T temperature, U specific internal energy, C_υ heat capacity at constant volume, t is the time, μ dynamic viscosity, β thermal coefficient of volume expansion and $\mathbf{u}$, $\mathbf{g}$ and $\mathbf{q}$, respectively, the velocity, gravity and heat flux vectors.

- Air inside the furnace admitted as an ideal gas, according to equations (1) and (2).
- Physical properties assumed constant and evaluated at the average temperature of 450 K, as shown in Table 1.
- Laminar, incompressible and Newtonian flow.
- SIMPLE algorithm in pressure-velocity coupling.
- Transient simulation until the convergence of the solution to the permanent regime;
- Equation of Continuity in laminar regime – equation (3).
- Momentum Equation in a laminar regime with the Boussinesq model for inclusion of field forces – equation (4).
- Energy Equation in laminar regime – equation (5).

According to [1] and [2] to simplify the modeling and numerical solution of heat exchanges by radiation on the mat, several hypotheses needed to be assumed:

- The furnace behaves as a closed system, in homogeneous media, at low velocities when compared to light velocity, not polarized, in thermodynamic equilibrium and with almost constant refractive index.
- The air flowing inside the furnace is considered a non-participant media or transparent to radiation.
- The surfaces inside the furnace behave as gray surfaces $(\alpha_{rad} = \varepsilon)$.
- The radiation phenomena occur in a quasi-equilibrium regime. This covers most of the engineering problems, according to [12].

From the assumed hypotheses, we have the application of the numerical methods for the evaluation of heat exchanges by radiation – FVDOM (Finite Volume Discrete Ordinates Method) and viewFactor (Surface to Surface – S2S). So that:

$$\hat{s}_i . \nabla I(r, \hat{s}_i) = \kappa(r) . I_b(r) - \beta_{rad}(r) . I(r, \hat{s}_i) + \frac{\sigma_s(r)}{4\pi} \sum_{j=1}^{n} w_j . I(r, \hat{s}_j) . \Phi(r, \hat{s}_i, \hat{s}_j) \tag{6}$$

$$q_{rad}(r) = \int_{4\pi} I(r, \hat{s}) . \hat{s} . d\Omega \cong \sum_{i=1}^{n} w_i . I_i(r) . \hat{s}_i \tag{7}$$

$$\sum_{j=1}^{N} \left[\frac{\delta_{ij}}{\varepsilon_j} - \left(\frac{1}{\varepsilon_j} - 1 \right) F_{ij} \right] . q_{rad_j} = \sum_{j=1}^{N} \left[\delta_{ij} - F_{ij} \right] E_{b_j} - G_{0_i} \tag{8}$$

$$F_{ij} = \frac{1}{A_i} \int_{A_i} \int_{A_j} \frac{\cos\theta_i \cos\theta_j}{\pi S^2} dA_i dA_j \tag{9}$$

, where $\hat{s}_i$ and $\hat{s}_j$ are the unit vectors in the directions i and j, r position vector, I intensity of radiation, I_b blackbody intensity of radiation, w_j quadrature weights FVDOM method, Φ scattering phase function, Ω solid angle, δ_{ij} Kronecker's delta function, ε and ε_j the emissivity, F_{ij} viewfactor, E_{b_j} black body emissive power, G_{0_i} external radiation that reaches the surface in analysis, S is the distance between the central regions the infinitesimal elements dA_i and dA_j, θ polar angle and κ, β_{rad}, σ_s, respectively, the absorption, extinction and scattering coefficients.

- For the use of the Finite Volume Discrete Ordinates Method (FVDOM) have the equations (6) and (7). That through an iterative process solves the RTE – equation (6) – for n directions, calculating simultaneously the intensity of radiation emitted by the walls and the intensity incorporated or emitted by the beam in participating media. The calculation process ends when the residuals of the coupled equations converge. In the end, the intensities of radiation $[I(r,\hat{s}_j)]$ calculated in equation (7), whose solution provides the q_{rad}.
- For the use of the viewFactor Model has the equations (8) and (9), respectively, to evaluate the heat exchanges by radiation and the view factors between surfaces.

Table 1. Physical Properties.

$\overline{T}$	450 K
ν	$3.239.10^{-5}\ \frac{m^2}{s}$
μ	$2.507.10^{-5}\ \frac{kg}{m.s}$
α	$4.72.10^{-5}\ \frac{m^2}{s}$
$\overline{\rho}$	$0.744\ \frac{kg}{m^3}$
C_p	$1021\ \frac{J}{kg.K}$
β	$2.264.10^{-3}\ K^{-1}$
Pr	0.686
Pr_t	0.7
g	$(0\ \ -9.81\ \ 0)\frac{m}{s^2}$

, where ν is the kinematic viscosity, α thermal diffusivity, C_p heat capacity at constant pressure, Pr and Pr_t, respectively, the Prandtl number and Prandtl turbulent number.

The definition of the physical and numerical model was based on measurements of furnace's geometric dimensions, temperature values and velocity of the mat in a similar industrial food furnace used for the pre-baking process of pizzas. This information also contributed to the mesh construction and the definition of initial and boundary conditions. Temperature values were collected by a non-contact infrared thermometer Raynger® of high performance, model MX4, with a laser sight, adjustable emissivity, temperature range between -30 ^oC and 900 ^oC, response time 250 ms, accuracy of $\pm 0.75\%$ and data acquisition system. The furnace geometric dimensions and the *Mat* transport time, to calculate its velocity, were obtained with the use of steel tape and digital timer.

Boundary Conditions

The initial and boundary conditions are defined according with to the real conditions of the identified patches. Table 2 a) b) and c) the boundary conditions used for the different surfaces. This table shows how to implement the physical conditions through typical commands of OpenFOAM®.

Table 2. a) Initial and Boundary Conditions.

Patch	p	U	T
Outlet	*calculated*	*inletOutlet*	$\nabla T = 0$
Inlet		$(0\ \ 0\ \ 0.1)$	310.15 K
Left Wall		$(0\ \ 0\ \ 0)$	$\nabla T = 0$
Right Wall			
Upper			
Burner Tube			573.15 K
Mat		$(0\ \ 0\ \ 0.1)$	336.65 K

Table 2. b) Initial and Boundary Conditions (continuation).

Patch	alphat	p_rgh
Outlet	*compressible::alphatWallFunction*	10^5 Pa
Inlet		*fixedFluxPressure*
Left Wall		
Right Wall		
Upper		
Burner Tube		
Mat		

Table 2. c) Initial and Boundary Conditions (continuation).

	G	IDefault	Q_r
Outlet	*Marshak Radiation*	*greyDiffusive Radiation*	*greyDiffusive Radiation viewFactor*
Inlet			
Left Wall			
Right Wall			
Upper			
Burner Tube			
Esteira			

The static pressure (p) is calculated from the total pressure excluding the field effect (p_rgh). The condition *fixedFluxPressure* defines the pressure gradient from the mass flow at the boundaries. This term is zero in the case of impermeable walls.

The velocity condition (U) for the region of Outlet, *inletOutlet*, is a mixed boundary condition. In case of positive flow, the condition is *zeroGradient* $(\nabla U = 0)$ and in the case of negative flow, the condition is uniform velocity and equal to (0 0 0), as specified in *inletValue*.

The mat temperature was estimated as a simple arithmetic average between the air inlet temperature (T = 310.15 K) and the outlet temperature of the final product on mat (T = 363.15 K), experimentally measured.

Alphat is turbulent thermal diffusivity (α_t). Calculated by the boundary condition *compressible::alphatWallFunction*, which gives a condition of turbulent diffusivity used to capture the effects near the wall in turbulent flows with low Reynolds number. It is important to emphasize that the solver used requires, as standard, the identification of this and other contour conditions, and also of the turbulent properties; even in laminar flows. These requirements aim, mainly, facilitate the process of inclusion of the turbulence models, in case of divergence of the simulation.

The boundary conditions for the radiation models are defined by the items G, IDefault and Q_r. The greatness G is incident radiation or irradiation, calculated from the temperature field of the previous time step through the standard boundary condition *MarshakRadiation*. IDefault is the intensity of radiation and the standard boundary condition is *grey Diffusive Radiation*. Q_r is heat exchanges by radiation, calculated through the standard boundary condition *greyDiffusiveRadiationViewFactor*. These boundary conditions provide a behavior of gray and diffuse body to the molded furnace and simplify the application of radiation models FVDOM and viewFactor. Emphasizing that only the radiation model viewFactor uses the last condition, Q_r.

Numerical Model

The free and open source software OpenFOAM®, version 2.4.0, was used in numerical simulation. The construction of the geometry is defined by *keypoints*, where the definition of mesh parameters is made in the preprocessor *blockMesh*. The resolution of algebraic linear equations, obtained by the discretization of the transport equations through the Finite Volumes Method, was performed by a specific solver for modeling, present on OpenFOAM®. Post-processing is done through another open source program – *paraView*.

The solver used is the *buoyantSimpleFoam*, which is characteristic for compressible, laminar or turbulent flow, and incorporated to the pressure-velocity coupling algorithm of the transport equations SIMPLE. Presents pre-implemented in its source code the mechanisms of heat exchange by radiation and compressibility models.

Mesh

Several commercial and free softwares may be used in computational mesh generation. However, the *blockMesh* utility of OpenFOAM® was chosen in this study for the mesh generation process. The mesh construction process using this utility is complex, because it involves several geometric calculations. However, it is capable of generating structured meshes and suitable to reduce the required computational power in the simulation. The use of the *blockMesh* utility to geometries of high complexity and with many details is not recommended, because the *blockMesh* decomposes the geometry in a set of one or more three-dimensional hexadecimal blocks.

Validation of Radiation Models

A simple test case, with radiation heat exchange only, was used to validate the radiation models FVDOM and viewFactor of OpenFOAM®.

The physical model of this case is a very simplified evacuated cavity, according to Figure 4. This two-dimensional cavity is composed of four surfaces of 1 m length. The left surface was at 100 K temperature and the other ones were at 1 K temperature. The cavity is evacuated and its walls were considered as black bodies. For this simple case, the analytical solution was known.

The cavity was simulated using the radiation models FVDOM and viewFactor in software OpenFOAM®. The physical and numerical conditions are quite similar to the one used in the furnace's physical model. The obtained numerical results were compared to those obtained through the analytical solution.

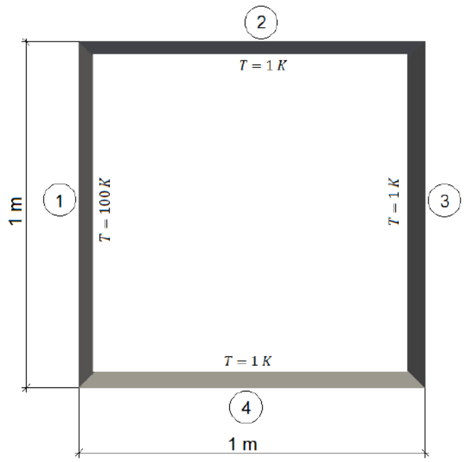

Figure 4. Physical conditions for validation of numerical radiation models.

Table 3 shows the values of view factors calculated using analytical expressions and those obtained through numerical computational simulation through the app *viewFactorsGen,* from OpenFOAM® package.

Table 3. View factors calculated using the analytical formulation and computer numerical simulation.

View Factors	Analytical	Numerical
F_{11}	0.000000	0.000000
F_{12}	0.292893	0.292893
F_{13}	0.414214	0.414214
F_{14}	0.292893	0.292893

The numerical evaluation of the viewFactor depends of choosing sample points can present larger errors on more complex geometries. In the validation case, it was observed a very good agreement between the analytical and numerical results.

Calculating the heat exchanges by radiation on the surfaces and the black body hypothesis, according [1], one can use the equation (10):

$$q_{rad\,NET,i} = \sum_{j=1}^{N} A_i.F_j.\sigma.\left(T_j^4 - T_i^4\right) \qquad (10)$$

where σ is Stefan-Boltzmann constant.

Table 4 presents the results for the heat exchanges net rate by radiation among the surfaces. Analytical and numerical computational simulation results using FVDOM and viewFactor radiation models are shown.

Table 4. Heat exchanges net rate by radiation per surface – analytical and numerical.

$q_{rad\,NET}$	Analytical [W]	Numerical	
		FVDOM [W]	viewFactor [W]
$q_{rad\,NET_1}$	-5.67	-5.67041	-5.67041
$q_{rad\,NET_2}$	1.66074	1.66358	1.66083
$q_{rad\,NET_3}$	2.3485	2.34326	2.34876
$q_{rad\,NET_4}$	1.66074	1.66358	1.66083

Analyzing these results one can observe that numerical results obtained in both radiation models presented a good agreement with the analytical results. The maximum deviation for the results analytical and numerical is from the order of 0.223%. Based on these considerations, both radiation models present physically consistent behavior and validated results for them simple case. So, the models are also used in the simulation of the real food furnace studied.

RESULTS AND DISCUSSION

For setting the element size/control volume was made a test of independence and mesh consistency. Nine mesh size tests are done using elements of 0.20 m and 936 points; 0.175 m and 1080 points; 0.15 m and 1904 points; 0.125 m and 3649 points; 0.10 m and 6120 points; 0.075 m and 14008 points; 0.06 m and 25368 points, 0.05 m and 43632 points and 0.04 m and 83160 points.

The tests of independence and mesh consistency were simulated considering the Boussinesq model for buoyancy forces. Radiation heat exchanges among walls and heat transfer with the external environment using conduction and environmental radiation were neglected. The physical properties and boundary conditions are presented on Tables 1 and 2 – except for the mat region, which is now admitted adiabatic $(\nabla T = 0)$.

The temperature field on the central region of the mat was used for analysis and comparison of the different mesh sizes. Figure 5 shows the temperature for the point $x = 0.5$, $y = 0$ and $t = 3600\,s$ of simulation for different mesh sizes.

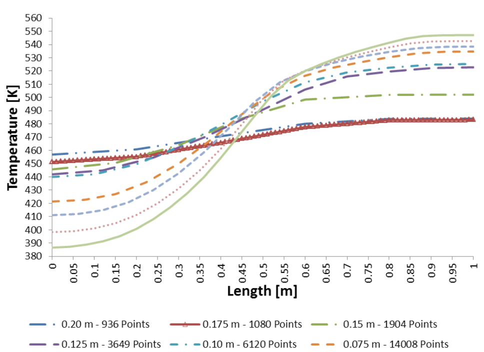

Figure 5. Temperature fields in the center of the mat for t=3600 s.

The analysis of Figure 5 shows that the refined meshes, with element sizes of 0.06 m, 0.05 m and 0.04 m, are suitable for the realization of the simulations. With maximum deviations in relation to the most refined mesh is from an order of 6.34% for the mesh with elements of 0.06 m and 3.02% for the mesh with elements of 0.05 m. So, considering the lower computational power requirement and shorter time demanding simulation, it was chosen the mesh size of 0.05 m and 43632 points. The Figures 6 and 7 illustrate the mesh with the chosen element size.

The entrance region of mat (*z* = *0*), showed in Figure 5, presents some convergence problems with mesh refinement. Although a refined mesh on this region could solve this problem it can also increase, significantly, the computation time. So, highlighting that the outflow conditions is the more relevant information on this simulation, the inflow conditions where not considered as essential for this analysis.

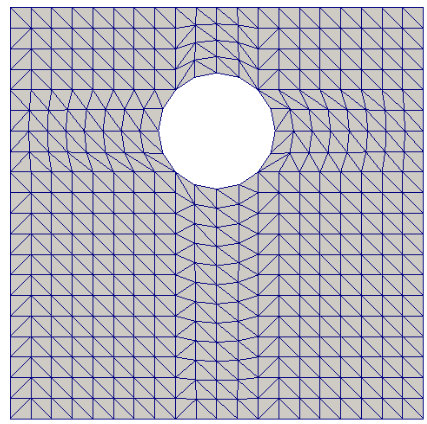

Figure 6. Frontal view of the computational mesh.

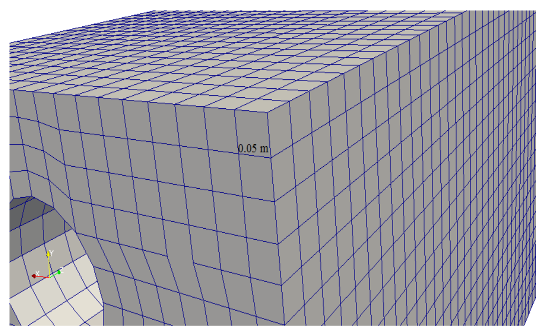

Figure 7. Isometric view of the computational mesh.

Applying the proposed physical model for the different radiation models, the heat transfer radiation and convection rates over the central region of the mat could be evaluated. Figures 8, 9 and 10 and Table 5 show some of these results.

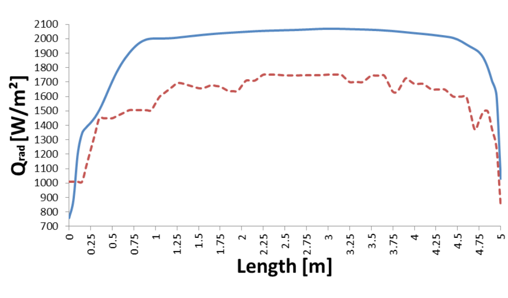

Figure 8. Radiation heat transfer on the mat for the different radiation models.

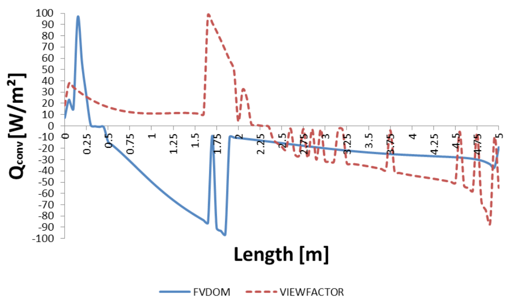

Figure 9. Convection heat transfer on the mat for the different radiation models.

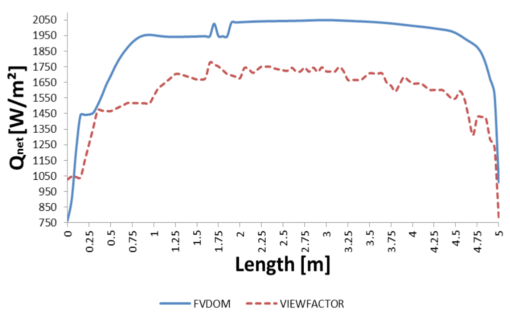

Figure 10. Net heat transfer on the mat for the different radiation models.

Table 5. Heat transfer by radiation and convection integrated in the mat.

	Q_{rad} [W]	Q_{conv} [W]	Q_{net} [W]
FVDOM	9144.82	-93.92	9050.90
viewFactor	7861.16	-19.59	7841.57

Figure 8 shows that the FVDOM model presented higher heat transfer radiation rates than the viewFactor mode. The variation is from order of 16.33% according to the reference by the integration of the data of Table 5. A justification for this high difference can be attributed to the viewFactor model uses a sampling process to calculate the view factors. This methodology, when applied to complex geometries presents problems of faces agglomeration and, consequently, higher errors.

Considering Figure 9 one can observe the fact of the convection heat flux is positive in the first half of the mat and negative in the second half when using the viewFactor radiation model. The same does not occur in the FVDOM model, where the heat flux is predominantly negative, i.e., the mat loses energy by convection in almost all its extension. The order of magnitude of the convection heat transfer on both radiation models is lower than that of radiation. Thus, it is observed that small oscillations on temperatures and velocities affect significantly the behavior of the convection heat transfer in this region and cause significant oscillations in its behavior. However, the analysis of the results presented in Table 5 shows that, in both radiation models, the mat has heat losses by convection.

Figure 10 shows the energy balance on the mat. It is observed that the heat transfer by radiation is significantly higher than that by convection one. This fact illustrates the importance and necessity of adequate modeling for this phenomenon. Table 5 shows a percentage difference between the models is 15.4%, using as reference the data integration.

Besides the inconvenience of greater deviations depending on its sampling points, the viewFactor radiation model presented some advantages and it was more effective on the proposed solution. The advantages considered are its best suitability the for the used physical boundary conditions associated with greater simplicity and higher convergence speed. However, it should be noted that more studies are necessary for its implementation, since both models, according to studies in [5], should have the same results.

Independently of the model of radiation used, a meaningfull challenge found in this work was the coupling of the boundary conditions of the processes of convection and radiation. The OpenFOAM® has functions that allow the coupling of convection and radiation. However, these available boundary conditions were effective only in situations where the heat transfer by convection and radiation has the same order of magnitude. When the heat exchanges by radiation are much larger than those of convection there is a divergence of the solution.

The influence of the turbulence modeling on the radiation heat transfer was evaluated in [13]. The conclusion is that turbulence modeling has little influence on heat exchanges by radiation, although it has a very significant effect on heat exchanges by convection. However, as the order of magnitude of the convection is much lower than that of radiation in this case, its effects could be considered as negligible on the mat. Some simulations need to be done to verify this hypothesis.

It is necessary to highlight that the boundary conditions used to establish fixed temperatures at the Inlet, Burner Tube and Mat and condition of the adiabatic surface at the regions of Outlet, Left Wall and Right Wall. Based on these conditions, the radiation models were used to evaluate the heat transfer rates by radiation on the surfaces of interest.

CONCLUSIONS

The FVDOM and viewFactor radiation models implemented on OpenFOAM® were validated based on a comparison of the numerical and analytical results for the studied cavity, according to Tables 3 and 4.

In the study of the furnace presented, it was observed that the heat transfer by convection is less significant than by radiation one. Thus, it is impossible modeling furnaces without the using a suitable model for evaluation of radiation.

In this study, the viewFactor radiation model proved to be more advantageous. It is quite simple and has a higher speed of convergence. Despite the advantages, higher errors can be expected in more complex geometries, considering its sampling process for calculation of the view factors.

Due to the differences of the intensities in heat transfer by radiation and convection, it is difficult to evaluate the latter. Small variations of temperatures, velocities and the turbulence parameters affect the behavior of convective heat transfer, inducing significant oscillations in their behavior.

As a reference for future works, one can highlight the inclusion of coupled boundary conditions for convection and radiation processes using the OpenFOAM®. This aim is especially important when the order of magnitude of the heat transfer by convection is from the same order of the radiation one. Other studies for evaluating the similarities, differences, limitations and applicability of the FVDOM and viewFactor radiation models of OpenFOAM® are also encouraged.

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